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# AICE* SURVEY OF USSR AIR POLLUTION LITERATURE

## Volume XIII

# TECHNICAL PAPERS FROM THE LENINGRAD INTERNATIONAL SYMPOSIUM ON THE METEOROLOGICAL ASPECTS OF ATMOSPHERIC POLLUTION

## PART II

Edited By

M. Y. Nuttonson

The material presented here is part of a survey of
USSR literature on air pollution
conducted by the Air Pollution Section
AMERICAN INSTITUTE OF CROP ECOLOGY

This survey is being conducted under GRANT R 800878
(Formerly R01 AP 00786)
OFFICE OF AIR PROGRAMS
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# PREFACE

The present volume constitutes Part II* of translations of papers presented in Leningrad during July 1968 at the International Symposium on Meteorological Aspects of Air Pollution. The original papers delivered at the Symposium were edited by Prof. M. E. Berlyand and published as a report in 1971 by the Hydrometeorological Publishing House in Leningrad.

The report contains a total of 40 papers, 37 of which are in Russian and three, in German, together with their accompanying abstracts. In this volume we present a collection of translations of a considerable number of papers from the original report. It is planned to publish translations of the remaining papers of this report in a subsequent volume.

A review article by T. A. Ogneva, "International Symposium on Meteorological Aspects of Atmospheric Pollution" (Izv. VGO**, Vol. 101, No. 4, 1969, pp. 395-396) provides interesting background material regarding the Symposium. For this reason we present our translation of Ogneva's paper in the following paragraphs.

"At the present time, considerable attention is being given to the study of atmospheric pollution in order to improve the sanitary status of water and air reservoirs in urban areas and workers' settlements and to intensify measures aimed at the preservation of nature. In working out the measures designed to decrease the pollution of air by noxious impurities, a special role is played by the consideration of meteorological factors, that substantially determine the behavior (dispersal) of impurities in the atmosphere. This problem was the subject of an International Symposium on Meteorological Aspects of Atmospheric Pollution, held in Leningrad at the A. I. Voeykov Main Geophysical Observatory on 22-31 July 1968. The organizers of the Symposium were the State Committee of the USSR Council of Ministers on Science and Technology (Scientific Council on the Problem 'Protection of the Air Reservoir from Pollution by Noxious Substances') and the Main Administration of the Hydrometeorological Service, Council of Ministers of the USSR.

"The Symposium was attended by scientists and specialists (meteorologists, hygienists, chemists, power engineers, metallurgists, etc.) from Bulgaria, Hungary, Vietnam, the German Democratic Republic, Poland, Rumania, Czechoslovakia, and the Soviet Union. Forty-five reports were delivered, and there was an animated discussion on the subjects of physical principles and methods of calculation of dispersal of industrial emissions in the atmosphere; meteorological parameters determining atmospheric diffusion and intensity of atmospheric pollution; procedures and equipment for observing atmospheric pollution, and experimental studies of pollution of the atmosphere by noxious impurities.

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* Part I can be found in Volume XII of the AICE Survey of USSR Air Pollution Literature.

** Izvestiya Vsesoyuznogo Geograficheskogo Obschestva, Tom 101, vip. 4, Iyul' - Avgust 1969.

"On the first day, M. Ye. Berlyand (Main Geophysical Observatory) reported on the status and prospects of development of meteorological studies of atmospheric pollution. He noted the following basic problems in the development of further research: study of meteorological conditions in the presence of heavy air pollution, including the mechanisms of turbulent exchange in the presence of inversions, a complex topography, and urban buildings; development of automatic and recording apparatus; study of the vertical distribution of noxious impurities; accumulation of observational data and development of methods of forecasting pollution, etc.

"In the report of I. L. Varshavskiy (State Committee of the USSR Council of Ministers on Science and Technology), 'Basic Trends of Scientific Research on Protection of the Air Reservoir from Pollution', the problems mentioned as the major ones involved the study of the biological action and hygienic importance of atmospheric pollutants, the influence of meteorological conditions on the distribution of noxious impurities in the atmosphere, the removal of noxious impurities from waste gases of industrial enterprises, and the removal of toxic components from the exhaust gases of internal combustion engines.

"Considerable interest was elicited by the report of M. S. Gol'dberg (A. I. Sysin Institute of General and Communal Hygiene) on the 'Hygienic Standards for the Maximum Permissible Content of Noxious Substances in Atmospheric Air.' He noted that hygienic standards worked out on the basis of experiments and actual laboratory and clinical studies constitute the scientific basis of environmental improvement measures in the struggle with atmospheric pollution, and make it possible to evaluate the results from the standpoint of providing the optimum living conditions for the population.

"Papers by a number of members of the Main Geophysical Observatory presented studies dealing with the physical validation of the procedure for calculating the pollution of the atmosphere with emissions of industrial enterprises and steam power plants, an investigation of turbulence in the lower 500-meter layer, an experimental study of pollution in industrial areas on the territory of the Soviet Union, the establishment of the relationship between meteorological conditions and air pollution in urban areas, the development of automatic methods of determination of atmospheric pollutants, etc. There were also reports on studies conducted in collaboration with Moscow University (S. M. Gorlin) in which the influence of irregularities of the earth's surface on the characteristics of the air flow was investigated in wind tunnels in connection with the problem of impurity diffusion.

"Members of the Institute of Experimental Meteorology (USSR) presented a series of reports on the study of diffusion of impurities and characteristics of turbulence from a 300-meter meteorological mast in Obninsk. Individual reports were also delivered by members of the Institute of Applied Geophysics (Ye. N. Teverovskiy), the Central Aerological Observatory (N. Z. Pinus), the

F. F. Erisman Scientific Research Institute of Hygiene (R. S. Gil'denskiol'd and B. V. Rikhter), and others.

"Specialists from Czechoslovakia (A. I. Vesecky, head of delegation), the German Democratic Republic (W. Warmbt, head of delegation), Poland (W. R. Parczewski, head of delegation) introduced the participants of the Symposium to the broad range of experimental research on the problem of atmospheric pollution. D. Szepesi (Hungary) reported on studies of meteorological conditions of turbulent diffusion, and G. I. Diaconescu (Rumania), on studies of thermal stratification of the atmosphere in connection with the pollution problem.

"All the participants of the Symposium came to the conclusion that at the present stage of the struggle with atmospheric pollution, the methods of purification and the construction of high stacks should be combined for the purpose of effectively utilizing the dispersing capacity of the atmosphere.

"The need for an extensive introduction of meteorological investigation of industrial projects and for the forecasting of air pollution was noted. One of the primary problems noted was that of validating and standardizing the methods of calculation of atmospheric pollution, the meteorological and hygienic procedures in studying the chemical composition of the atmosphere, and the meteorological parameters determining this composition."

It is hoped that the papers presented in this volume will be conducive to a better appreciation of the meteorological-air pollution investigations conducted in the USSR and in a number of the Soviet-block countries. As the editor of this volume I wish to thank my co-workers in the Air Pollution Section of the Institute for their valuable assistance.

M. Y. Nuttonson

April 1972

# AUTOMATION OF INFORMATION PROCESSING INVOLVED IN EXPERIMENTAL STUDIES OF ATMOSPHERIC DIFFUSION

A. S. Zaytsev (USSR)

From Glavnoe Upravlenie Gidrometeorologicheskoy Sluzhby Pri Sovete Ministrov SSSR. (Chief Administration of the Hydrometeorological Service Under the Council of Ministers of the USSR.) "Meteorologisheskie Aspekty Zagryazneniya Atmosfery". (Meteorological Aspects of Air Pollution.) Sbornik dokladov na mezhdunarodnom simpoziume v Leningrade - Iyul' 1968 g. (Reports delivered at the International Symposium in Leningrad - July 1968.) Pod redaktsiey d-ra fiz.-mat. nauk M. E. Berlyanda. (Edited by Prof. M. E. Berlyand.) Gidrometeorolgicheskoe izdatel'stvo, Leningrad, p. 130-136 (1971). (Hydrometeorological Publishing House, Leningrad, (1971).)

Experimental studies of atmospheric diffusion involve the necessity of recording the change of meteorological parameters and impurity concentrations in time and space. They include measurements of temperature, wind, turbulence characteristics, and concentration of a large number of noxious impurities. The data obtained require various types of treatment, which consumes considerable time when manual methods are employed. Modern experimental studies have become such that a relatively short observation time (of the order of minutes and hours) requires processing of the data obtained that occupies a considerably longer period of time (of the order of days and months).

In the organization of effective control of atmospheric pollution, particular importance is assumed by the efficiency of the treatment of the information obtained. The problem of automating the measurements of noxious impurity concentrations also includes the creation of automatic gas analyzer instruments, but this paper will discuss only the automation aspects of the processing. In view of the fact that in studies of atmospheric diffusion the primary information obtained is in different forms (electric signal, weighed sample of dust on filter, stereopairs of smoke plume photographs, etc.), the solution of the problem of automating the processing of such information, in contrast to, for example, aircraft meteorological information [1], must be carried out by using different methods.

There are two approaches to solving the problem of automation of the processing. One involves primary processing directly under field conditions and the presentation of information in a form that is suitable for further machine processing. The second involves only the recording of measurable quantities under field conditions followed by processing under stationary conditions.

Data on the time and space variability of atmospheric parameters make it possible to evaluate the detail with which their measurements should be carried out (for example, in airplane studies, to obtain details of the distribution of meteorological elements, it is necessary to have information every

20-30 m along the vertical and every 1-2 km along the horizontal [1]). For impurity concentration fields under urban conditions, the frequency of discrete measurements is difficult to establish at the present time, so that it is necessary to strive for a continuous recording.

In view of the above, it appears expedient to use the second approach to solving the problem of automating the processing of data on atmospheric pollution and some other meteorological parameters.

Since the chief forms of information carriers are graphical tracings on photographic paper or a strip chart, one cannot help reading the ordinates with a certain discreteness. Industrial devices designed for this purpose use optical reading methods employing electron tubes or photodiode matrices and are designed for automatic reading without the participation of an operator. Also known are analog computers that solve individual problems with the aid of recordings on tape. A considerable limitation is imposed on the use of automatic devices by requirements regarding the quality and quantity of the tracings on strip charts. The number of tracings is usually limited to one or two, and they should not intersect. The line thickness is strictly standardized, there must be no grid of any kind on the chart, the recordings must not be discontinuous, should be sufficiently smooth, etc. It follows from the above that the experimental data obtained under expeditionary conditions, which are frequently quite complex, can satisfy the enumerated requirements in only rare exceptions. It thus becomes necessary to develop methods of semiautomatic reading of graphical information, which involve the participation of an operator who follows the recording on the chart.

Known techniques of this kind are very limited [2, 3, 9] and do not solve the problem of automation of the processing as a whole. Considering the possibility of direct input into a digital electronic computer and the relative simplicity of the development and execution of the scheme, a method of encoding in digital code on telegraph tape was chosen [4] involving the use of industrial schemes and units, which made the system more versatile. In line with technical requirements, the measurement accuracy is ±0.5% of the measured value, the measurement frequency, 4-10 Hz, the tape speed, 1-5 m/hr (the speed being limited chiefly by capabilities of the operator), and the tape width, up to 300 mm.

The use of the method of semiautomatic digitizing made it possible to remove a number of substantial limitations on the recording. It is possible to process the tapes in the presence of a large number of intersecting tracings, which can even be discontinuous, and there are no limitations on the thickness, steepness and color of the tracings. The system consists of a series of units: 1) conversion of the ordinate to an electrical analog (ordinate-analog unit), 2) unit of measurement of the electrical analog with representation of the data in digital code, 3) conversion of digital codes and synchronization, and 4) recording unit. The recording unit employed was to tape puncher. In view of the fact that in many problems it is sufficient to obtain the ordinates in the form of digits, a variant of the recording scheme was developed involving digital printing on paper tape in the decimal system with a frequency of 2 ord/sec. The use of this device substantially accelerates the processing. Thus, whereas several hours is needed for manual processing of an oscillogram of overloads for a single airplane flight, only half an hour is necessary when the semiautomatic device is used. The evaluations performed showed that on the average, the variant with digital printing accelerates the processing by a factor of 10, and with perforation, by a factor of 40.

As was stated above, experimental studies of atmospheric diffusion yield different types of information, including those requiring preliminary processing before their processing can be automated. Thus, the preliminary processing of data of the stereogrammetric photography of smoke plumes is carried out in a photographic laboratory, then the coordinates of the smoke plume boundaries are digitized on stereocomparators, the information being presented in a form suitable for input into digital computers (on punched cards or punched tape) for subsequent calculations. The developed methods of automatic recording of dust concentration [5] also assume a preliminary photometering of tape filters under laboratory conditions, following which the information obtained can be automatically processed by using the methods described above.

The second approach to automation - initial treatment of information under field conditions with output on punched tape - can be effectively used for recording the wind velocity profile in the surface layer (for example, calculation of contacts, use of moving averages for a given time segment, encoding and output of mean velocities on punched tape), and also for automating pilot balloon (particularly reference observations [10]).

Switching immediately to the results of processing and calculations by means of the above-described methods, we should note that the recordings of airplane overloads have been the ones processed most effectively at the present time. Measurements of overloads of the airplane's center of gravity are carried out in expeditionary studies of atmospheric pollution. An analysis of data from observations in the area of a number of large-capacity emission sources is given in adequate detail by P. A. Vorontsov [6]. For this reason, only some aspects of the semiautomatic processing of the data will be described below. The procedure used in the flights usually includes sounding of the atmospheric boundary layer with ascent and descent in plateaus, at each of which the airplane overloads are recorded for 3 minutes. The overload gauge used is an MP-66 instrument, with loop oscillographs being used as recorders. The observational material in the area of the Shchekino State Regional Electric Power Plant (SREPP) (1963) and the Moldavian SREPP (1965) were digitized semiautomatically, and computations of the turbulence characteristics (using the Lyapin-Dubov method) were carried out on the "Ural-4" digital computer:

$$k=\frac{|\overline{w'}|\,\bar{\tau}V}{2},\quad L=2\bar{\tau}V. \qquad (1)$$

where k is the turbulence coefficient, and $|\overline{w'}|$ is the mean value of fluctuations of the vertical wind velocity component:

$$w'=\frac{1}{PF(H,\omega)}\,\frac{1}{N}\sum_{i=1}^{N}|h_i-\bar{h}|. \qquad (2)$$

where $h_i$ is the running ordinate of the overloads, $\bar{h}$ is the mean ordinate, $F(H,\omega)$ is the transfer function, V is the airplane speed, $\tau$ is the preservation time of fluctuations of the same sign, L is the characteristic eddy scale, P is a calibration constant, and N is the number of ordinates on the given plateau.

Processing of the recordings of airplane overloads permits the calculation of the fluctuations of the vertical wind velocity component w'. Figure 1 shows averaged vertical profiles w' during the period of studies near the indicated SREPP's. The observations were made chiefly in the daytime, and the w' values obtained correspond to a regime of developed turbulence. A certain increase in fluctuations at a height of 500 m is due to the combined influence of thermal and dynamic factors on the development of turbulence. Large w' values in the area of the Shchekino SREPP are apparently due to the influence of the features of the underlying surface.

It is known that measurements of overloads are of little use in the study of long-period fluctuations, i. e., large-scale eddies, in which an airplane can move upward and downward without any appreciable overloads. Another limit of the region are high frequenceis (approximately 7-10 $sec^{-1}$), which cause small overloads that the gauge cannot record. Thus, airplane measurements permit the study of only a part of the spectrum of the turbulence scale.

Figure 2 shows mean profiles of sizes of turbulent disturbances L. The large values for the Shchekino SREPP apparently are also due to the influence of the topography. There is a fairly clear-cut tendency toward an increase of the scales with height, due to a decrease of the influence of the earth's surface with increasing height. The character of the increase of L with height is not uniform; the greatest increase is observed in the lower layers. In the daily variation (Fig. 3), a characteristic feature is a wider-scale spectrum during intermediate hours, when turbulence develops or damps out. During the day, eddies of smaller size predominate, due to the influence of thermal turbulence, which leads to the breaking up of large eddies.

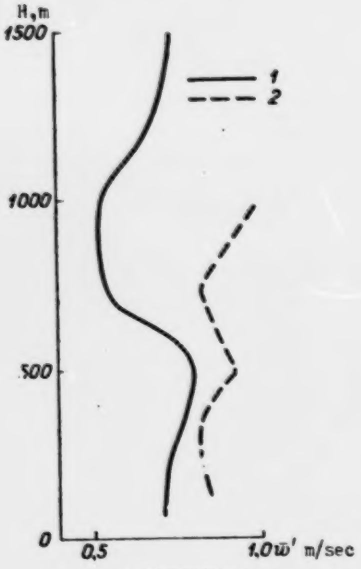

Fig. 1. Vertical profiles of fluctuations of the vertical wind velocity component for areas of the Moldavian SREPP (1) and Shchekino SREPP (2).

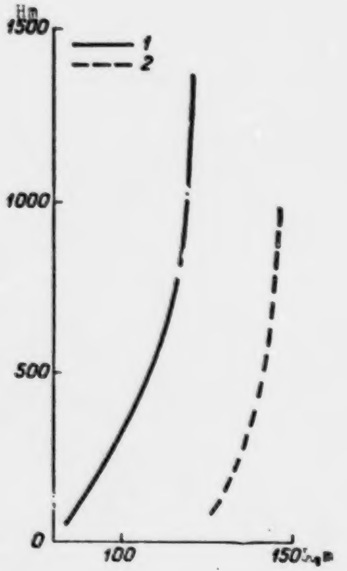

Fig. 2. Mean profiles of the size of turbulent disturbances for areas of the Moldavian SREPP (1) and Shchekino SREPP (2).

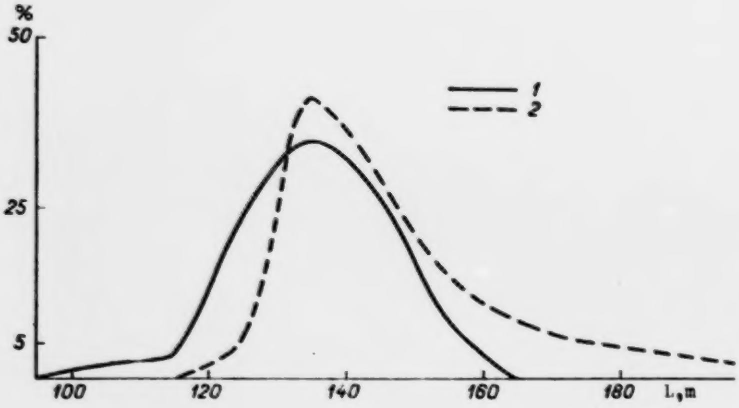

Fig. 3. Frequency of sizes of turbulent disturbances in the area of the Shchekino SREPP during the day (1) and during intermediate hours (2).

Analysis of data on the turbulence coefficient showed that in the course of the expeditions, the characteristic values $k \approx 25\text{-}30\ m^2/sec$. Maximum values were observed at a height of approximately 500 m.

Semiautomatic methods were used to process other measurements as well. Experimental studies of atmospheric diffusion involve measurements of oscillations of the wind direction. The gauge used is an M-45 wind recorder. Wind direction recordings obtained in the course of a study of atmospheric pollution near a synthetic fiber plant were processed by using a variant of the above-discribed unit with output of the data on a digital printer. In addition, calculations of the variance of the wind velocity were carried out for different averaging intervals, and the values obtained were compared with the stability parameters of the atmospheric surface layer. Results of the analysis are given in [8].

In working out the procedure for determining hydrogen sulfide and carbon disulfide [7], a dynamic sulfur dioxide concentration dispenser and a GKP-1 automatic gas analyzer were used. Digitizing of the recording of concentrations before and after the absorber was carried out semiautomatically and demonstrated the high effectiveness of the use of such processing methods in studies involving gas analyses.

In conclusion, it should be noted that work on the automation of measurements and processing of observational materials on atmospheric pollution and necessary meteorological parameters has only begun and will be continued as part of a program of development of methods and instrumentation aimed at organizing an effective control of atmospheric pollution and meteorological support of such work.

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### *A. S. ZAITSEV*

## THE AUTOMATION OF INFORMATION TREATMENT IN CONNECTION WITH EXPERIMENTAL INVESTIGATIONS OF ATMOSPHERIC DIFFUSION*

Experimental investigations of atmospheric diffusion include the measurements of meteorological and turbulent air current characteristics and also pollutant concentrations by quick-response sensors. The automation of data treatments is connected with primary treatment, information memorization, and subsequent treatment on electronic computers.

The employment of helicopters and cars supplied by automatic instruments for air pollution investigation leads to the necessity of prompt processing of information in stationary conditions. For this purpose, the method of automatic and semiautomatic treatment of information read out from oscillographic tapes is used.

For some problems, memorization of coded measured quantities is possible directly in field conditions. In connection with this, the methods of automatic reading of sensors, information memorization, calculation of averages for a definite time period and data coding on punched tape are used.

With this, the final data treatment is carried out on electronic computer according to beforehand compiled programs (calculations of turbulence coefficient, wind characteristics, etc.). The calculations and analysis of turbulent coefficient and of the parameter which characterizes the wind direction variability are carried out on obtained measurement results, and records of automatic gas analyzers are treated, too.

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* Editor's note: The abstract is presented as given in English with the original Russian article.

# MICROMETEOROLOGICAL CHARACTERISTICS OF ATMOSPHERIC POLLUTION CONDITIONS

T. A. Ogneva (USSR)

From Glavnoe Upravlenie Gidrometeorologicheskoy Sluzhby Pri Sovete Ministrov SSSR. (Chief Administration of the Hydrometeorological Service Under the Council of Ministers of the USSR.) "Meteorologisheskie Aspekty Zagryazneniya Atmosfery". (Meteorological Aspects of Air Pollution.) Sbornik dokladov na mezhdunarodnom simpoziume v Leningrade - Iyul' 1968 g. (Reports delivered at the International Symposium in Leningrad - July 1968.) Pod redaktsiey d-ra fiz.-mat. nauk M. E. Berlyanda. (Edited by Prof. M. E. Berlyand.) Gidrometeorolgicheskoe izdatel'stvo, Leningrad, p. 137-146, (1971). (Hydrometeorological Publishing House, Leningrad, (1971).)

The dispersal of impurities in the atmosphere depends considerably on the meteorological conditions in its lowest, surface layer. This paper discusses some results of studies made at the A. I. Voyeykov Main Geophysical Observatory on the meteorological characteristics of the surface layer, sometimes called the micrometeorological characteristics [8].

I. In the Soviet Union, systematic micrometeorological observations are being conducted at so-called heat balance stations. The set of observations includes measurements in the 0.5-2 m layer of differences in air temperature, water vapor pressure, wind velocity, and also measurements of the temperature and humidity of the upper 20-centimeter layer of the soil. These observations make it possible to supplement the existing experimental data (obtained chiefly during short-term expeditionary observations) on the time and space relationships (within the boundaries of the Soviet Union) of the chief characteristics of turbulent mixing - the thermal stratification of the surface layer and the turbulence coefficient at a height of 1 m.

The distribution of stations whose observational material was used in this paper is shown in Fig. 1.

It should be noted that these observations are conducted on platforms of weather stations located mainly in open, comparatively flat areas on surfaces with grassland vegetation characteristic of this particular landscape zone. All the data considered here pertain to such surfaces. Table 1 gives characteristic values of temperature differences at the level of 0.5-2 m ($\Delta t$) in the warm season for daytime (1 P.M.) and nighttime (1 A.M.) in the main landscape zones. These values may be considered characteristic, since they were obtained on the basis of daily observational data averaged over several years (from 4 to 10) and taken at individual stations. The following regularities of variation of characteristic values of $\Delta t$ in time and space may be noted.

In the daytime, the sign of $\Delta t$ is positive during all the months of the warm season, and this promotes turbulent mixing; on the contrary, at night, an inversion is observed that decreases the turbulence intensity.

In the daytime, the lowest values of Δt, which do not exceed 0.5°C., are characteristic of the forest zone; to the north of the latter (in the tundra) and to the south (in steppes, deserts), the values of Δt increase, and in the deserts exceed 1°C.; at night, the zonal distribution is less distinct, and in the forest, steppe and desert zones, the inversions do not exceed 0.5°C.; they reach 1°C. only in the zone of piedmont steppes and in floodplains.

In comparison with the vertical temperature gradients of the free atmosphere, the characteristic gradients of the surface layer in the warm half of the year are two orders of magnitude (50-100 times) greater, and are pronounced superadiabatic gradients in the daytime and inverted gradients at night.

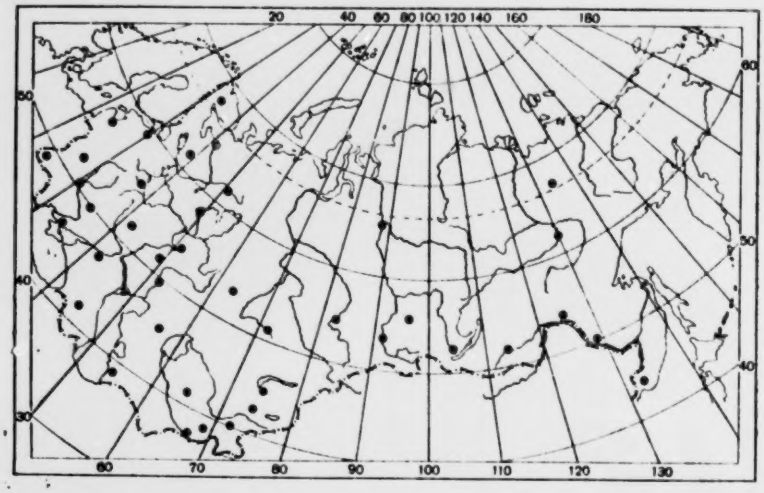

Fig. 1. Map of the stations.

The sufficiency of characteristic Δt values can be seen from Fig. 2. As an example, the latter shows diagrams of the seasonal variation of frequencies of different Δt values in the daytime and at night for weather typical of a given zone. They pertain to stations located in the desert, a typical steppe, and in zones of coniferous and mixed forests. From the diagram it is evident that at night, independently of the landscape zone, in 60-70% of cases there is a predominance of Δt's which in absolute value do not exceed -0.5°C., and that their values amounting to less than -1°C. occur in only 10-15% of the cases; this proportion is also characteristic of the seasonal variation. In the daytime, the frequency of the different values shows a more pronounced variation in seasonal course and depends on the landscape zone. In the desert, Δt>1°C. is observed in 60-70% of the cases from May to October. In the steppe zone, such Δt values are observed in 60% of the cases in August only, and in all of the remaining months,

Table 1

Characteristic Values of $\Delta t$ in Different Landscape Zones.

| Zone | V | VI | VII | VIII | IX | X | V | VI | VII | VIII | IX | X |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 A.M. | | | | | | 1 P.M. | | | | | |
| Pretundra thin forest | | | —0,6 | —0,8 | —0,3 | | | | 0,9 | 0,7 | 0,4 | |
| Coniferous forest | —0,3 | —0,5 | —0,5 | —0,4 | —0,3 | —0,2 | 0,5 | 0,5 | 0,5 | 0,4 | 0,3 | 0,1 |
| Mixed forest | —0,5 | —0,6 | —0,4 | —0,4 | —0,4 | —0,2 | 0,4 | 0,4 | 0,4 | 0,3 | 0,2 | 0,1 |
| Deciduous forest | —0,4 | —0,4 | —0,4 | —0,4 | —0,4 | —0,4 | 0,4 | 0,5 | 0,5 | 0,4 | 0,4 | 0,3 |
| Floodplains | —0,5 | —0,6 | —0,7 | —0,7 | —0,5 | —0,4 | 0,4 | 0,6 | 0,6 | 0,5 | 0,4 | 0,3 |
| Steppelike grassland | —0,6 | —0,6 | —0,6 | —0,6 | —0,5 | —0,4 | 0,6 | 0,6 | 0,8 | 0,8 | 0,7 | 0,5 |
| Piedmont steppes | —0,9 | —1,1 | —1,1 | —1,0 | —1,0 | —0,8 | 0,6 | 0,5 | 0,7 | 0,9 | 1,0 | 0,8 |
| Grassland steppes | —0,4 | —0,5 | —0,5 | —0,4 | —0,4 | —0,3 | 0,6 | 0,7 | 0,6 | 0,5 | 0,5 | 0,4 |
| Typical steppes | —0,4 | —0,4 | —0,4 | —0,4 | —0,5 | —0,3 | 0,7 | 0,9 | 0,9 | 0,8 | 0,7 | 0,4 |
| Deserts | —0,3 | —0,4 | —0,5 | —0,5 | —0,5 | —0,4 | 1,1 | 1,2 | 1,2 | 1,1 | 1,0 | 0,7 |

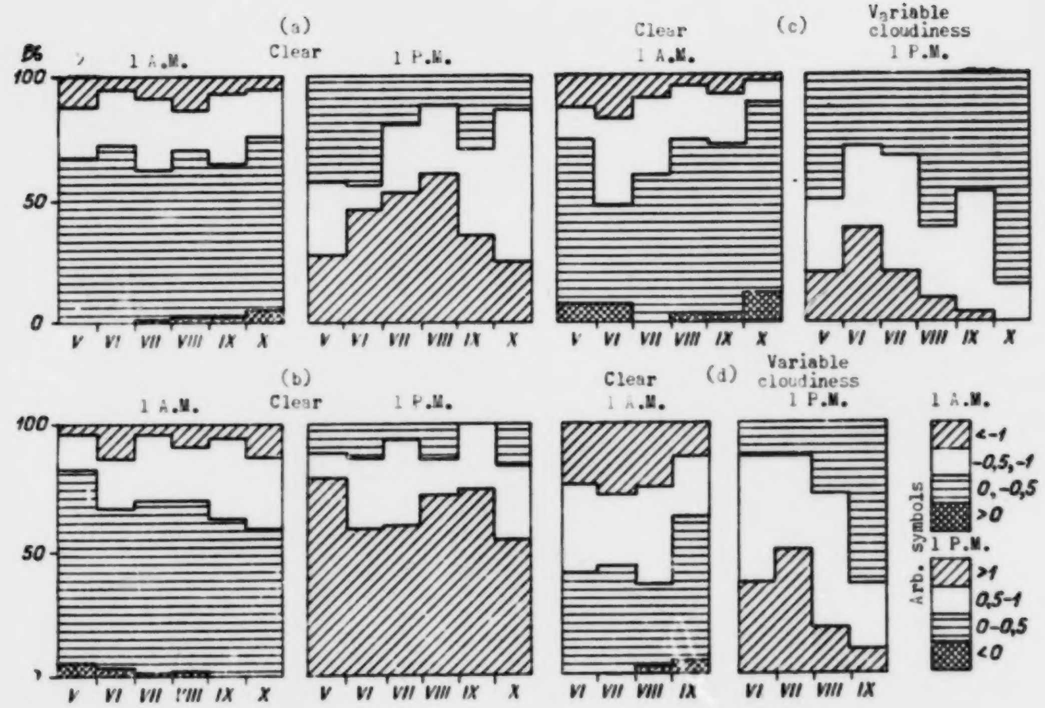

Fig. 2. Frequency of different values of $\Delta t$.
a - steppe, b - desert, c - zone of mixed forests, d - zone of coniferous forests

their frequency is much lower. In the forest zone, the seasonal course of the frequency of the values $\Delta t > 1$°C. is also pronounced, but its greatest values do not exceed 50%. The frequency of the values $\Delta t < 0.5$°C. also changes with the zone, increasing from the desert to the forest zone. As is evident from the diagram, positive $\Delta t$ values at night and negative ones during the day are observed very seldom.

Extreme values of $\Delta t$ selected from observational data for 3-5 years (Table 2) show that $\Delta t_{max}$ do not exceed 5°C. and on the whole, depend little on the landscape zone. Only a tendency toward an increase of $\Delta t_{max}$ in the zones of insufficient humidification (steppes, deserts) can be observed. The minimum $\Delta t$'s are greater than the maximum ones in absolute value. As a rule, extreme $\Delta t$ values are observed during the summer months.

Table 2

Extreme Values of $\Delta t$

| Zone | $\Delta t_{max}$ | Month | $\Delta t_{min}$ | Month |
|---|---|---|---|---|
| Pretundra thin forest | 2,5 | VII | —3,7 | VIII |
| Coniferous forest | 3,4 | VIII | —4,3 | VI |
| Mixed forest | 3,3 | VII | —3,7 | VII |
| Deciduous forest | 2,4 | VIII | —3,6 | IX |
| Floodplains | 3,2 | VI | —3,7 | VI |
| Steppelike grasslands | 3,3 | VI | —3,6 | IX |
| Piedmont steppes | 3,7 | V | —4,6 | V |
| Grassland steppes | 3,7 | VI | —4,7 | VI |
| Typical steppes | 3,8 | VI | —4,7 | V |
| Desert | 4,5 | VIII | —4,3 | I |

As we know, the formation of any given values of temperature (lapse rates) is determined by the proportion of the components of the heat balance and its main component, the radiation balance. The proportion of the components of the heat balance may be characterized in a simplified manner by the radiation balance, wind speed and state of humidification of the surface.

Analysis of the relationship between $\Delta t$ and the radiation balance [6] shows that the temperature differences increase with increasing radiation balance and decrease with increasing wind speed in the zone of forests and steppes for both positive and negative values of the radiation balance. In the desert zone, the largest positive differences do not arise at weak wind speeds, but at a speed of 2-4 m/sec. A change of sign of the difference in the forest zone takes place at higher values of the radiation balance than in the zone of steppes and deserts. As the wind speed increases, the change of sign is also observed at a higher value of the radiation balance as compared with weak speeds.

II. When characterizing the turbulent exchange, it is necessary to consider not only the values of the differences in the temperature of the surface air layer, but also the wind speed. A complex characteristic of the thermal stratification of the atmosphere is the Ri number or its analog, the parameter $\Delta t/u_1^2$ which is widely used in the USSR [7]. Its characteristic values for the main landscape zones during the day and at night in the warmest month (July) are shown in Table 3. On the whole, the parameter $\frac{\Delta t}{u_1^2}$ increases from the forest zone to the desert zone from 0.10 to 0.25 in the daytime and from -0.09 to -0.17 at night (its values were calculated for cases of more or less developed turbulence, when $u_1>1$ m/sec). This means that as a result of the influence of thermal stratification, the characteristic values of the turbulence coefficient at a height of 1 m during the day increase 1.5-2-fold in the forest zone, 2-2.5-fold in the steppe zone, and 2.5-3-fold in the desert zone. At night, the effect is approximately the same.

III. The observational materials of the heat balance stations make it possible to obtain the distribution of the turbulence coefficient $k_1$ in space and time at a height of 1 m. V. P. Gracheva [4] plotted a map of characteristic values of $k_1$ over the territory of the Soviet Union for July during hours of strongest heating of the surface (1 P.M.). The $k_1$ values were calculated by the heat balance method for a period of 5-10 years.

The turbulence intensity is distributed by zones, increasing from north to south. The highest values of $k_1$, up to 0.25 $m^2$/sec, are characteristic of the areas of steppes and deserts; in the forest zone, the turbulence coefficient decreases to 0.15-0.10 $m^2$/sec. The mean monthly $k_1$ values are fairly stable; they change only slightly from year to year, in the range of 10-15% (the standard deviations amount to 0.02-0.03). July is the month of the strongest turbulence, as is evident from Fig. 3 [3], which shows the annual course of $k_1$ for the steppe and forest zones in the daytime and at night. No marked differences in the annual course of daytime $k_1$ values are observed in the different zones; there are differences only in absolute values and in amplitude, which in the forest zone is greater than in the steppe zone. The nighttime values of $k_1$ have an annual course opposite to that of the daytime ones, i.e., in summer a minimum is observed, and in winter, a maximum. These relationships are determined by both the influence of thermal stratification and the character of the wind speed.

Table 3

Limits of $\Delta t/u_1^2$ Values in Different Landscape Zones in July.

| Zone | 1 A.M. | 1 P.M. |
|---|---|---|
| Forest | −0,09−0,16 | 0,10−0,15 |
| Steppe | −0,13−0,16 | 0,17−0,19 |
| Desert | −0,15−0,17 | 0,21−0,25 |

The method widely used in the Soviet Union, of determining $k_1$ on the basis of measured lapse rate data (using the results of the semiempirical theory of turbulence or the heat balance equation) makes it possible to obtain the turbulence intensity for specific periods of time, in particular, when conducting surveys of pollution in cities or at individual industrial facilities. Figure 4 shows a graph of the daily course of $k_1$ obtained by G. P. Rastorguyeva from data of observations in the forest and forest-steppe zones in summer and winter. In summer, the daily amplitudes of $k_1$ are twice as high or more than those in winter. The largest values of $k_1$ occur in the midday hours.

IV. Wind is one of the chief meteorological parameters determining the diffusion of impurities. This parameter (as compared with other meteorological elements) is subject to the strongest variations under the influence of different kinds of obstacles such as topography of the terrain, building system, and vegetation. Wind variations caused by the topography are studied experimentally and are characterized by certain general regularities. A number of observational results are reported in the monograph [5]. The latter gives a table showing that the greatest speed variations are observed at the tops and in the upper portions of windward slopes, where the speed increases by 30-70%, and in valleys and lower parts of slopes through which the wind does not blow, where it decreases by 20-30%. At night, the speed variations are greater than during the day. As the wind speed increases, its differences in different topographical forms decrease. The wind direction also undergoes substantial changes in a dissected area, manifested in particular forms of the wind rose.

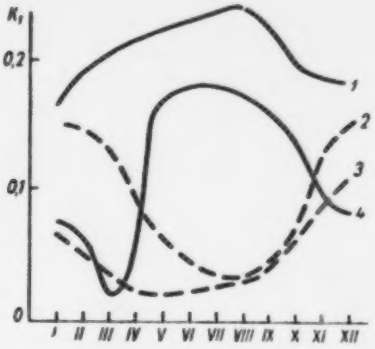

Fig. 3. Annual course of $k_1$ in the steppe zone during the day (1), at night (2) and in the forest zone during the day (4), and at night (3).

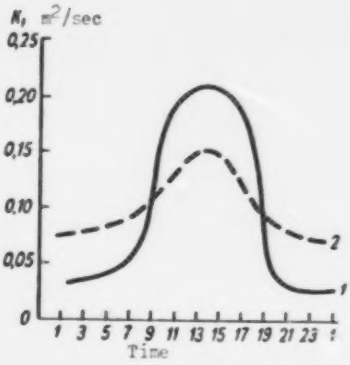

Fig. 4. Daily course of $k_1$ in summer (1) and winter (2).

In surveys of pollution of specific areas, the program of work includes special observations of the wind variation. I. I. Solomatina conducted such observations in the area of the Shchekino SREPP during the winter and summer periods and obtained microclimatic corrections for this area. As illustrated in Table 4, they amounted to 30-50% in the concave topographic forms (points 4-6) and lower parts of the slopes. The speed differences decrease with height over flat and dissected terrain.

Table 4

Ratio of Wind Speed at Observation Point to Speed over Open Flat Terrain.

| Wind Direction | Height, m | Points | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| NE and NNE | 1 | 0,8 | 1,1 | 0,9 | 0,9 | 0,5 | 0,7 |
| | 4 | 0,9 | 1,2 | 1,0 | 1,0 | 0,6 | 0,9 |
| SW and SSW | 1 | 0,8 | 0,9 | 0,8 | 0,8 | 0,7 | 1,0 |
| | 4 | 0,9 | 1,0 | 0,9 | 0,9 | 0,7 | 1,0 |

V. In analyzing and calculating the diffusion of impurities, it is essential to have information on the character of the stability of the wind direction as an indicator of turbulence. Experimental studies of this parameter in expeditions investigating atmospheric pollution and the data correlation carried out by V. P. Gracheva [2] made it possible to draw the following conclusions:

1) the standard deviation of the wind direction $\sigma$ changes over a range of 20° in the course of 20 minutes;

2) $\sigma$ decreases with increasing wind speed;

3) the thermal stratification has a substantial influence on $\sigma$; as the instability increases, the wind gustiness increases sharply, and as the inversion intensifies, it decreases;

4) as the averaging period increases, $\sigma$ grows, this growth being most pronounced for short periods (for example, as the period changes from 20 to 40 minutes, $\sigma$ increases by 25%, and from 40 to 60 minutes, by only 10%;

5) correlation of data for different areas of the Soviet Union shows that these relationships are generally universal and fit into the dependences shown in Fig. 5 (the figure illustrates the relationship of $\sigma$ to $u_1$ for different values of $\Delta t$.

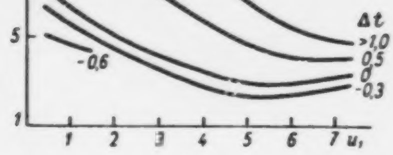

Fig. 5. Relationship of to $u_1$ for different t's.

VI. The development of conditions of impurity dispersal in cities is greatly influenced by the meteorological regime of the city. There are known results of studies of changes in thermal regime which are due to the influence of the urban building system and of changes in transparency conditions which are due to industrial emissions, as a result of which a heat island forms above the city. Such studies are now also being conducted during surveys of atmospheric pollution in specific cities.

The data of Table 5 were obtained by G. P. Rastorguyeva in an industrial city with a modern building system and a topography with some points exceeding others by 100 m, and with isolated depressions containing water reservoirs. The table lists values of air temperature differences at a height of 2 m measured at a weather station (located on the outskirts of the city) and in different parts of the city at night. These data confirm the presence of warmer air in the city as compared with the outskirts. It is essential to note that a marked lowering of the air temperature was observed in lower topographic forms with a natural surface.

Table 5

Values of Air Temperature Difference at a Height of 2 m at Night Based on Data of Observations from a Weather Station and at Various Points of a City

| Place of Observation | $\Delta t$ | Place of Observation | $\Delta t$ |
|---|---|---|---|
| Suburburban Areas | 0,1 | Low relief (soil) | −3,7 |
| City streets | −1,2 | Low relief (asphalt) | −2,1 |
| City squares | −1,9 | | |

The distribution of the air temperature at night in the city surveyed shows that its highest values coincide with the most built-up parts of the city and with the highest places, and the lowest values, with low places. The temperature contrast within the confines of a city with linear dimensions of 20 x 20 km was 7°C. when its values in depressions were taken into account, and 3°C. when they were neglected.

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*T. A. OGNEVA*

## MICROMETEOROLOGICAL CHARACTERISTICS OF AIR POLLUTION CONDITIONS*

Some investigation results of micrometeorological characteristics which influence the pollutant dispersion in the atmosphere are considered in this report. Information on air temperature gradient in the lower layer of two meters, received on systematic measurement data, is cited. Its variation in annual and daily course in different geographical zones on the territory of the Soviet Union and frequencies of different values of extreme temperature gradient are shown. Close connection of gradients with radiation balance is revealed.

The regularities of turbulence coefficient variation on the height of 1m in time and space are considered; a map of its values at 1:00 p. m. in July is given, from which latitudinal variations are seen, turbulence coefficient in southern regions of the country being twice as large as in nothern regions.

A correlation table is given which characterises wind velocity changes in different relief forms. Wind direction stability as an index of turbulent mixing intensity is discussed. A diagram built on experimental data received in different regions is cited. It is shown that wind direction variation increases with instability growth and decreases with wind velocity increasing.

Some data on variation of air temperature regime under the effect of urban regions are reported. The largest differences in comparison with rural areas are observed in building quarters and also on concave relief forms.

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* Editor's note: The abstract is presented as given in English with the original Russian article.

# STUDY OF THE INFLUENCE OF IRREGULARITIES OF THE EARTH'S SURFACE ON THE AIR FLOW CHARACTERISTICS IN A WIND TUNNEL

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From Glavnoe Upravlenie Gidrometeorologicheskoy Sluzhby Pri Sovete Ministrov SSSR. (Chief Administration of the Hydrometeorological Service Under the Council of Ministers of the USSR.) "Meteorologisheskie Aspekty Zagryazneniya Atmosfery". (Meteorological Aspects of Air Pollution.) Sbornik dokladov na mezhdunarodnom simpoziume v Leningrade - Iyul' 1968 g. (Reports delivered at the International Symposium in Leningrad - July 1968.) Pod redaktsiey d-ra fiz.-mat. nauk M. E. Berlyanda. (Edited by Prof. M. E. Berlyand.) Gidrometeorolgicheskoe izdatel'stvo, Leningrad, p. 147-161, (1971). (Hydrometeorological Publishing House, Leningrad, (1971).)

## Introduction

In studies of turbulent diffusion it is usually assumed that the underlying surface is comparatively flat and the air flow parameters, which influence the diffusion of an impurity, depend only on the height. Such a distribution of the parameters is appreciably altered by the presence of various types of obstacles on the earth's surface and especially by a relief. The collection under natural conditions of data that permit one to take into consideration the influence of the topography on the impurity diffusion processes involves major difficulties. For this reason, studies are now being conducted on the application of numerical methods and electronic computers to the study of the influence of obstacles on the characteristics of air flow [1].

Significant possibilities in the solution of this problem are due to the use of wind tunnel simulation, which, as demonstrated by many years' experience, has proved itself in applications to problems of aerohydromechanics. However, this path was found to have its own fundamental and technical obstacles. In the first place, they pertain to the finding of similarity criteria necessary and sufficient for the transition from tests on models in a wind tunnel to natural conditions. In the second place, it was found very difficult to produce in a wind tunnel a flow with a variable intensity of a turbulence similar in structure to atmospheric turbulence. This applies in particular to the reconstruction of high turbulence intensities or of a gradient turbulent flow in a considerable portion of the test section of the tunnel while retaining a spectral composition similar to an atmospheric turbulent flow.

This paper presents results pertaining to the creation in wind tunnels of a variable turbulence of the forward flow to the influence of turbulence on the aerodynamic characteristics of various bodies [2], and also to studies of disturbances of the velocity field and turbulence during flow past different kinds of obstacles. The experiments were conducted by the authors* in the large A-6 wind tunnel of the Scientific Research Institute of Mechanics, Moscow State University, and published in part in [3].

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*Measurements of turbulence intensity were carried out under the direction of L. I. Arafailova.

## Influence of Initial Turbulence on the Aerodynamic Characteristics of Various Bodies

Problems of the influence of turbulence intensity $\varepsilon = \frac{\sqrt{\overline{u'^2}}}{u}$ of the forward flow on the aerodynamic characteristics of various bodies have long attracted the attention of researchers. One problem of particular interest was that of the influence of turbulence intensity and Reynolds Re number on the characteristics of the lift of an airplane wing. In 1930-1940, these questions were widely studied in this country and abroad. However, for a number of reasons, including a small range of variation of Re numbers and $\varepsilon$, a generally inadequate level of aerodynamic measurements, etc., it was impossible to find any general regularities in the influence of these parameters. However, in recent years, this agreement began to be observed in the non-coincidence of results of experiments on physically identical models in tunnels, even on models identical in aerodynamic contour. A systematic application of principles of the similarity theory to the Reynolds equation indicates the existence of a dependence of the stream pattern on the degree of turbulence of external flow. These facts made it necessary to return to a detailed and thorough study of the problems of influence of turbulence intensity and Re number.

First, the methods of determination of the degree of turbulence and, in particular, of its longitudinal component were analyzed. The analysis showed that in the case of measurement of the intensity with a hot-wire anemometer, the frequency characteristic of the latter should have a very wide range, from 0 to tens of kilohertz. When a hot-wire anemometer is not used to measure low frequencies (up to 200-300 Hz), the measured $\varepsilon$ may be smaller than the true value, by a factor of more than 2. When the turbulence intensity is determined by an indirect method from results of sphere tests for drag or from the difference in pressures in front of this sphere and behind it, the sphere diameter $D_s$ (for small values of $\varepsilon$) should be no less than 0.1-0.12 of the diameter of the test section of the tunnel, $D_{ts}$.

The dependence of the turbulence intensity $\varepsilon$ in percent of the critical Reynolds number $Re_{cr}$ found experimentally for a sphere has the form

$$\varepsilon = \frac{10^{-5}}{Re_{\text{кр}}\left(0{,}1\,\frac{D_{\text{ш}}}{D_{\text{р.ч}}}\right)^{1/3}}.$$

A refinement of the method of determining the turbulence intensity made it possible to account for the difference in characteristics obtained in different tunnels for the same model. The change in the turbulence of the forward flow was found to have a substantial effect on the stream pattern around the body. For example, as $\varepsilon_0$ changes by 0.2% (from 0.1 to 0.3), the lift coefficient $c_{y\ max}$ for a TU-104 airplane increases by 10%, and the maximum lift/drag ratio of an AN-24 airplane decreases by more than 15%.

In the past, a series of experiments involving measurement of the critical Reynolds number $Re_{cr}$ for a sphere in the atmosphere, in particular, the known studies of Millikan and Klein [4] showed the measured $Re_{cr}$ to be independent of the weather conditions. The value of $Re_{cr}$ obtained from measurement data is greater than all the measured values of this number in wind tunnels and comes quite close to the number given by measurements in a wind tunnel with a very small degree of turbulence. For this reason, wind tunnels are designed to produce the smallest possible degree of turbulence of the outer flow. The methods of reducing the initial flow turbulence essentially amounted (for a closed wind tunnel) to decreasing the turbulence at the approaches to the honeycomb and nozzle by installing nets in front of the honeycomb. This made it possible to reduce the external degree of flow turbulence to a minimum.

However, the prewar studies of Taylor [5] and other authors revealed that the drag of bodies in air depends not only on the magnitude of the fluctuation velocities but also on the turbulence structure. J. I. Taylor proposed that the ratio of the sphere diameter to the characteristic length of turbulence be taken as the characteristic of the turbulence structure for flow around a sphere. From these points of view, one can account for the mentioned experiments of Millikan and Klein by the very minute values of this ratio in atmospheric experiments.

Our objective includes the simulation of flow around obstacles commensurate in size with the mean characteristic scale of turbulence in the atmosphere. Therefore, the influence of the degree of outer flow turbulence will be entirely different. Experimental data on the nature of the influence of the degree of turbulence on the stream pattern in the case of comparable size of obstacles and size of a typical eddy will be given below. In our studies, a wide variation of turbulence intensity in the test section was achieved by installing nets of different drags at the exit from the wind tunnel nozzle. In addition, it was possible to obtain a uniform velocity field over the entire test section and a very small gradient of turbulence change along the length of the test section. This fact was particularly important and set our experiments apart from work done in the past.

The relationship between the intensity of the longitudinal turbulence component $\varepsilon$ (in percent) to the drag coefficient of the nets mounted on the edge of the nozzle may be expressed by

$$\varepsilon = 2{,}55\xi^2,$$

where $\xi$ is the drag coefficient.

To determine the turbulence scale and the spectral energy distribution, measurements were made with a DYSA hot-wire anemometer with frequency cutoff. The turbulence scale $L_t$ was calculated from the formula $L_{\text{т}} = \frac{u_0}{f_{\max}}$, where $u_0$

is the velocity in m/sec, and $f_{max}$ is the frequency at which the energy maximum is located. As is evident from Fig. 1, obtained from experiments in an A-6 wind tunnel, the turbulence scale at small values of $\varepsilon$ has a size of the order of the tunnel diameter. As the degree of turbulence increases, it decreases sharply, then remains practically constant. This is due to the mounting of nets at the entrance, since in this case the turbulence scale will be determined not only by the tunnel diameter, but also by the mesh size of the nets. Knowledge of the dependences similar to the one shown in Fig. 1 makes it possible to estimate the ratio of the size of the obstacle studied to the turbulence scale, and to compare it with the ratio prevailing in natural conditions.

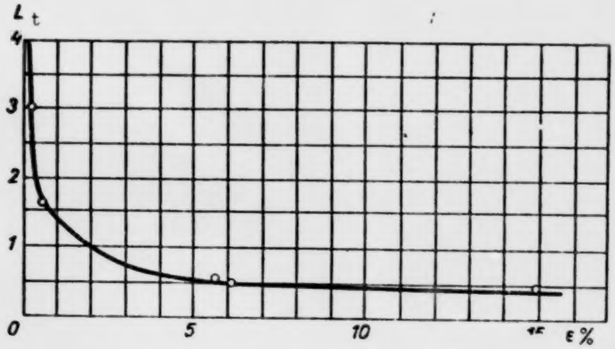

Fig. 1. Dependence of turbulence scale on turbulence intensity.

When it is necessary to produce a vertical gradient of the velocity field and turbulence, one can use the same nets and low drags in the form of corners located at irregular intervals along the vertical. The vertical gradient character necessary for experiments with land obstacles was found on the basis of experiments with a screen of variable surface roughness at different Reynolds numbers (up to $Re = 5 \times 10^6$) and different turbulence intensities of the forward flow.

The most complete evaluation of the structure of flows may be made by comparing their power spectra. Treatment of the results of such measurements showed a weak dependence of a considerable portion of the spectrum (for different values of the wave number k) on the type of measurement, perhaps with the exception of the case of small degree of turbulence at the entrance. For comparison, Fig. 2 shows data ($f(k)$ being the spectral function and $\nu$ the viscosity) obtained in a meteorological wind tunnel, a tidal basin, and in the atmosphere above a wavy sea surface [6] and also the results of our measurements in the A-6 tunnel for the following cases: (a) hollow tunnel, $\varepsilon_0 = 0.2\%$, $u_{av} = 20\text{-}30$ m/sec; (b) $\varepsilon_0 = 5\%$, $u_{av} = 10\text{-}20$ m/sec; (c) $\varepsilon_0 = 5\%$, screen with abrasive $x = 1480$ mm, $u_{av} = 10$ m/sec; (d) $\varepsilon_0 = 5\%$, smooth screen, $x = 3500$ mm, $u_{av} = 10$ m/sec; (e) $\varepsilon_0 = 5\%$, screen with abrasive, x = 3500 mm, $u_{av}$ = 10 m/sec.

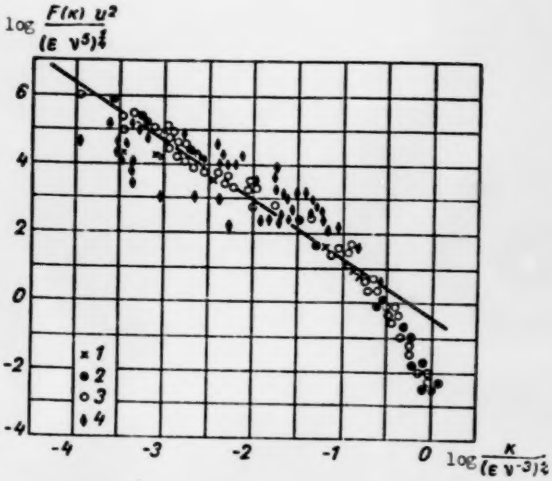

Fig. 2. Dependence of spectral function on wave number.

1 - wind tunnel, 2 - tidal basin, 3 - atmosphere above wavy sea surface, 4 - A-6 wind tunnel.

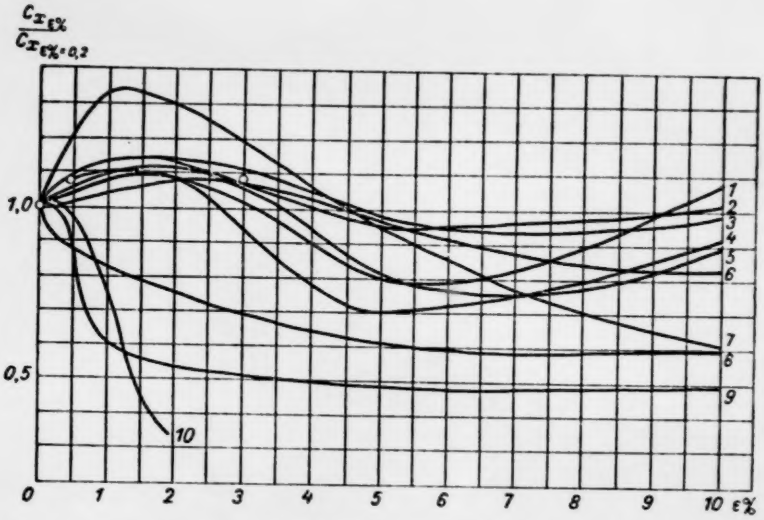

Fig. 3. Dependence of relative resistance of various bodies on the turbulence intensity of forward flow.

1 - sphere on screen (Re = $4 \times 10^6$), 2 - flat plate, 3 - cylinder above stall (Re = $4 \times 10^5$), 4 - sphere above stall (Re = $r \times 10^5$), 5 - cube (Re = $4 \times 10^5$), 6 - beam (Re = $3 \times 10^5$), 7 - car on screen (Re = $4 \times 10^6$), 8 - sphere on screen, 9 - cylinder below stall (Re = $2 \times 10^5$), 10 - sphere below stall (Re = $2 \times 10^5$); circles denote flat plate (old experiments).

As is evident from the figure, the results obtained are in mutual agreement, but our measurements give an appreciable scatter of points due to large values of the bands in the band-pass filter employed.

In order to study the influence of the degree of turbulence of the forward flow in the presence of comparatively small changes in the ratio of the obstacle size to the characteristic turbulence scale, we studied a broad category of bodies including streamlined (wings, airplanes) and bluff ones (sphere, cylinder, plate, cube, etc.). These experiments (Fig. 3) showed the presence of a stall of aerodynamic characteristics with respect to the $\varepsilon$ number, somewhat analogous to the stall with respect to the Re number. They also showed that for a number of bodies, simulation with Re number may be replaced by simulation with the $\varepsilon$ number. For example, at low Re numbers and high $\varepsilon$ values one can obtain drag values for a sphere, cylinder, etc. corresponding to large (above-stall) Re numbers and small $\varepsilon$ values. This fact substantially extends the possibilities of study in tunnels where it is difficult to achieve substantial Re numbers.

The influence of turbulence on aerodynamic characteristics depends on the shape of the body and the Re number. However, the general tendency lies in the fact that the drag of bodies in a flowing medium with sharp stalling (for example, a flat plate placed perpendicular to the flow or a model of a house with a pointed roof) is not sensitive to the initial flow turbulence.

## Study of Flow Around Land Obstacles - Results of Simulation

The A-6 MGU wind tunnel has an open test section of elliptical cross section measuring 4.0 x 2.4 m with a length of 4.0 m. The parameters of undistorted forward flow in the test section of the tunnel are characterized by the following quantities: the nonuniformity of the velocity does not exceed ±0.5%, the sidewashes in the horizontal and vertical planes are equal to ±0.3, and the critical Re number for the sphere $D_s$ = 150 mm. $Re_{cr} = 3.7 \times 10^5$ (from hot-wire anemometer measurements, $\varepsilon$ = 0.1-0.15%). Models of ground installations were mounted on a flat screen simulating the underlying surface. Different turbulence and velocity conditions in the flow incident on the model were produced by the indicated method using nets mounted on the edge of the nozzle. Measurements of the velocities and sidewashes in the vicinity of the models were made with a six-wave TsAGI probe, and those of the turbulence intensity, with a hot-wire anemometer.

Model of an isolated (two-dimensional) hill. The model studied had a cross section in the shape of an isosceles trapezoid with the following dimensions: length of base, 1500 mm; height, 100 mm; length of upper side, 500 mm; span, 2000 mm. The model was made of wood and polished, which corresponds to a height of roughness prominences of approximately 10-15 μm. A diagram of the placement of the model in the test section is given in Fig. 4.

When a weakly turbulent uniform flow ($\varepsilon_0$ = 0.3%) flows around the model, the velocity change in the vicinity of the model follows the configuration of the hill. On the forward slope, an acceleration of the flow reaching up to 10% of the velocity of the forward flow on the upper plane is observed. In the rear part of the hill, because of the diffusor effect, a deceleration is observed reaching 20-30% near the "ground". The zone of decelerated flow extends over approximately one "height" of the hill. A change in the range of $1 \times 10^6$-$4.1 \times 10^6$ in Re numbers calculated from the length of the base of the hill had practically no effect on the nature of the velocity distribution.

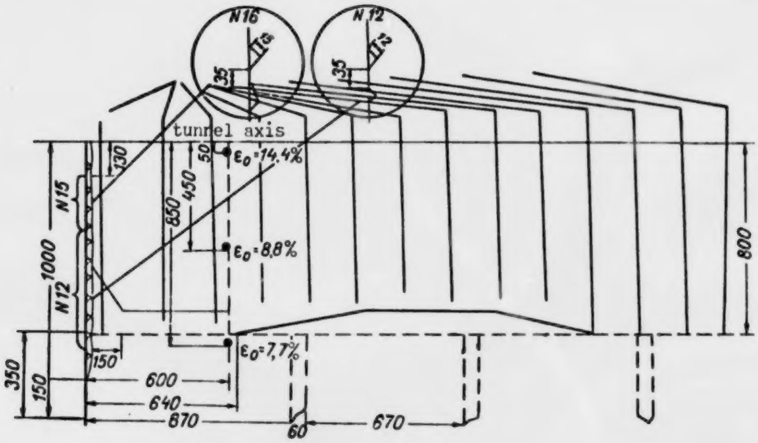

Fig. 4. Diagram of arrangement of corners, nets and model of isolated hill in A-6 wind tunnel, and dimensions of cross sections in which the flow parameters were measured.

Studies of the velocity distribution in the immediate proximity of the hill surface were made by means of a special rack of 30 Pitot tubes which made it possible to obtain the velocity profile starting at 8 mm from the surface. Results of experiments at Re numbers of $2.1 \times 10^6$ and $3.15 \times 10^6$ were in mutual agreement and showed that, as was to be expected, near the surface the deceleration of the velocity intensifies, reaching 15-25% on the forward slope, up to 30% on the upper surface, and up to 50% of the velocity of the forward flow in the afterbody. The regions of strong deceleration extend to a height equal to 0.5 of the height of the model (in the afterbody) and up to 0.2 on the forward slope of the hill.

The vertical mean velocity profiles near the surface (Fig. 5) differ substantially in the zones of low deceleration and acceleration from the velocity profile for the case of a turbulent boundary layer (according to the "1/7" law), shown in this figure ($z$ being the height and $\delta$ the height of the boundary layer). The deviations are particularly appreciable in the lower half of the boundary layer; in the upper part, this difference does not exceed 10% of the velocity of the forward flow.

The direction of the flow as a whole follows the configuration of the hill. In the forward (confusor part), the sidewash is positive (up to 8±10°); in the diffusor part, negative (up to 8°), and equalized very rapidly.

The change of the initial turbulence is monotonic in character and barely noticeable. In the region of acceleration, a certain decrease of $\varepsilon$ is observed, and in the diffusor region, there is an increase. Here, as in the case of velocity distribution, no dependence on the Reynolds number is observed. Results of experiments using the same hill model but with an appreciable turbulence of the forward flow (up to $\varepsilon \approx 8-9\%$) and different Re numbers (up to Re = $2.1 \times 10^6$) are shown in Fig. 6.

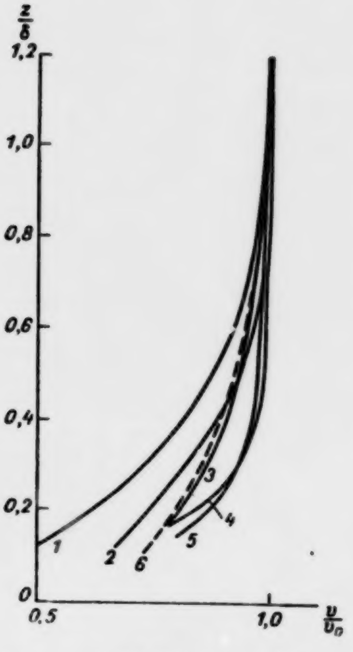

Fig. 5. Distribution of wind velocities in different cross sections above the hill.

1 - norm, 2 - behind the hill, 3 - forward slope, 4 - upper surface, 5 - in front of the model, 6 - $\left(\frac{v}{v_0}\right) = \left(\frac{z}{\delta}\right)^{1/7}$.

As is evident from the figures, in the case of large initial turbulence, the disturbances introduced by the model extend over a smaller region than for small $\varepsilon_0$ values. The influence of Re number is also very slight in this case. This may be explained chiefly by the fact that the dimensions of the model in the direction normal to the flow are small compared with its longitudinal dimensions. An analogous picture obtains in the case of flow around thin wings under small angles of attack. For example, as Re numbers change from $1.8 \times 10^5$ to $1.65 \times 10^6$ and $\varepsilon$ simultaneously changes from 0.3 to 3%, the value of the lift coefficient $C_x$ of such wings remains unchanged, attesting to a virtual constancy of the distribution of circulation, and, in particular, of the velocity above the wing. In our case, local velocity changes different from zero are "reinforced" by the screen and manifest themselves perceptibly only in regions along the normal that are bounded by the "height" of the model. Let us note in conclusion to this part of the experiments that studies under natural conditions also indicate the smallness of the disturbances introduced by gentle hills into the air flow above them.

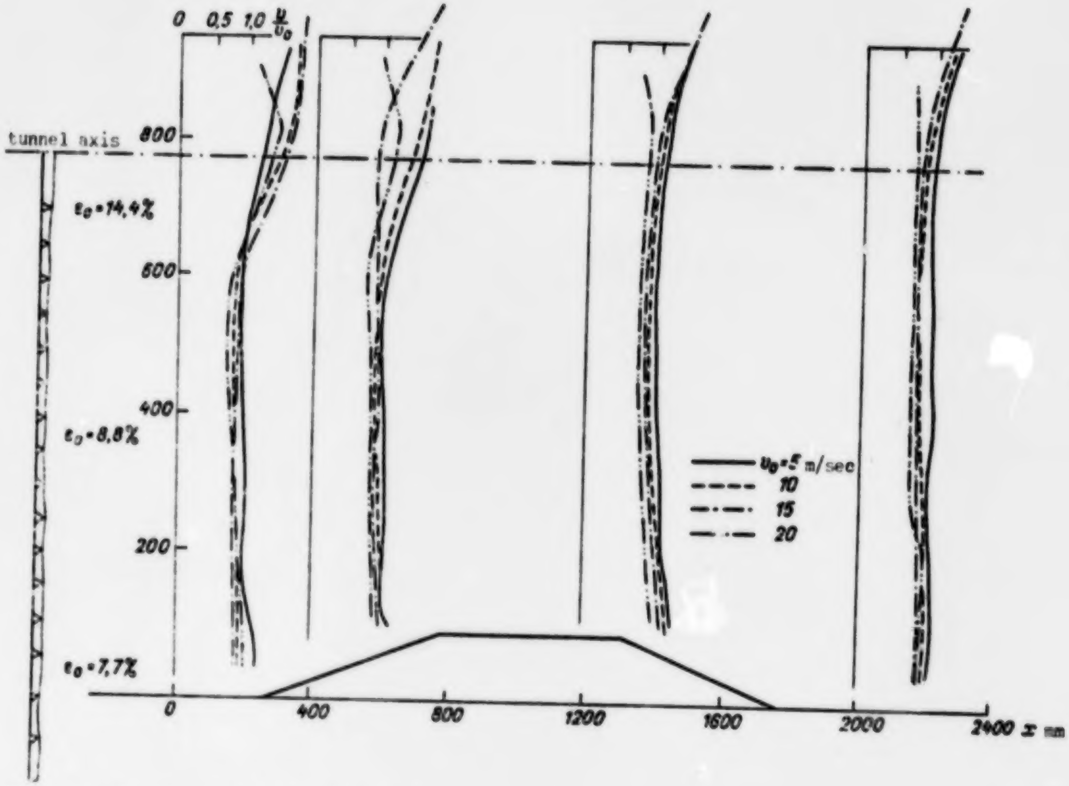

Fig. 6A. Distribution of relative velocity above the hill model at different velocities of the forward flow.

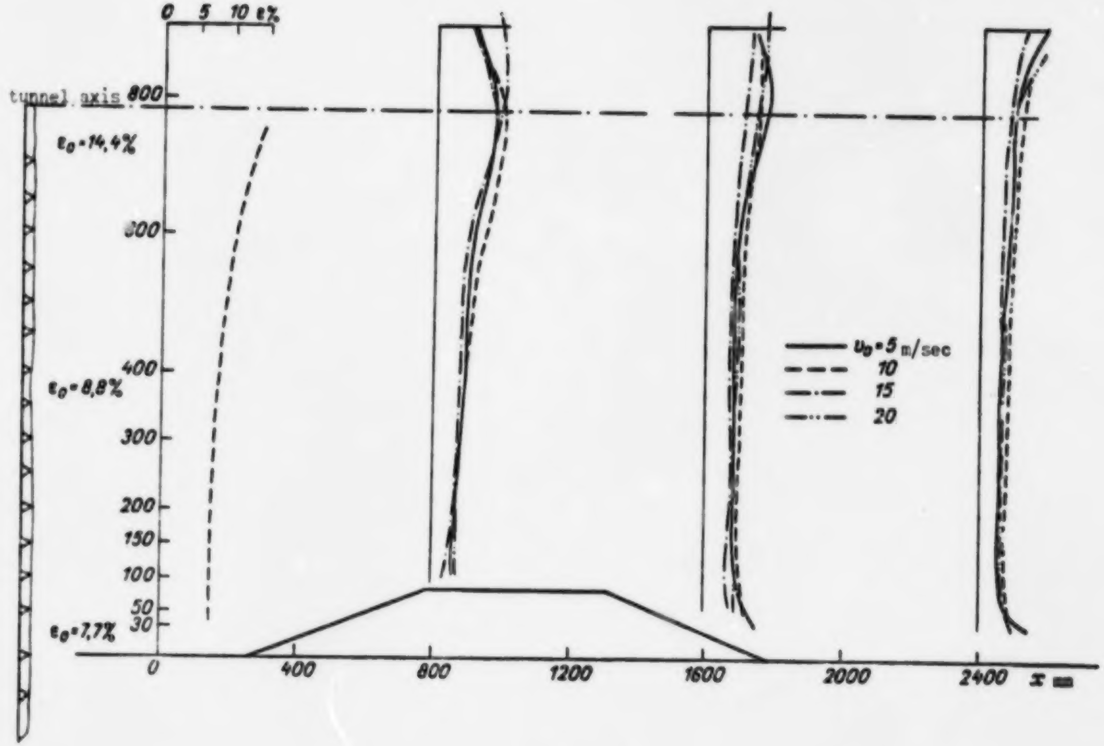

Fig. 6B. Distribution of longitudinal component of turbulence above the hill model at different velocities of forward flow.

The velocity field of the longitudinal component of turbulence was also studied above a three-dimensional hill. The model consisted of a truncated elliptical cone and had as its base an ellipse with axes of 1340 and 1080 mm, and in the upper part, an ellipse with axes of 880 and 660 mm; the height of the hill model was 60 mm. The model was made of wood and polished.

Fig. 7 shows the distribution of the degree of turbulence along the middle of a three dimensional hill for $\varepsilon_0$ values of 0.2 and 4%. As is evident from the figure, at a height of 0.3H, the influence of the initial turbulence in front of the obstacle is clearly visible. It is interesting to note that behind the hill, the maximum degree of turbulence is the same in both cases. Comparison of the distribution of the velocity and degree of turbulence shows that the velocity minima correspond to a maximum of the degree of turbulence, and the velocity maxima, to a minimum of the degree of turbulence. Comparison of the zones of velocity field and degree of turbulence above the three-dimensional and the two-dimensional hill and also above a wedge-shaped protrusion shows that, as expected, the disturbances introduced by the three-dimensional hill are more monotonic in character, and the distortion zone is somewhat smaller.

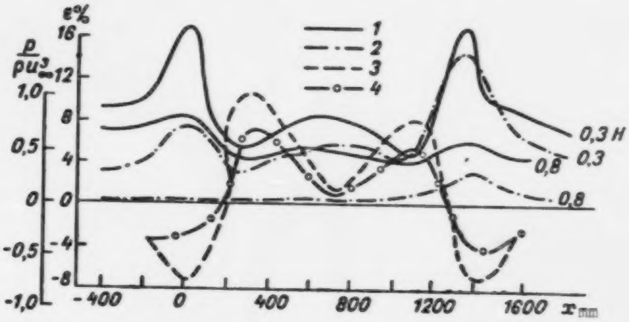

Fig. 7. Distribution of the degree of turbulence at heights of 0.3 H and 0.8 H for $\varepsilon_0$ = 4% 1) and $\varepsilon_0$ = 0.2% 2) and of the normal surface pressure for $\varepsilon_0$ = 4% 3) and $\varepsilon_0$ = 0.2 4) along the middle of a three dimensional hill.

Models of urban building systems. The study was made on models of two types of urban building systems: "flat" houses of a few stories (in the old blocks of Leningrad) and modern buildings (multistoried, with large gaps between them) (Fig. 8). The experiments involved the study of the influence of the models on the character of the flow above them as a function of the turbulence of the forward flow; the velocities within city blocks with modern building systems were found as a function of the wind direction and turbulence of the forward flow.

In the flow around the model of the system of "flat" buildings of a few stories, the deceleration of velocity and change of the turbulence intensity were found to be insignificant. The disturbance includes a relatively small region above the model, below a straight line with an inclination of 4°, with the origin of coordinates at a distance of 0.25 of the length of the model from its forward part. In the flow around the model of the modern building system, the deceleration of the velocity is more substantial, and the region of increased turbulence is located above the entire model.

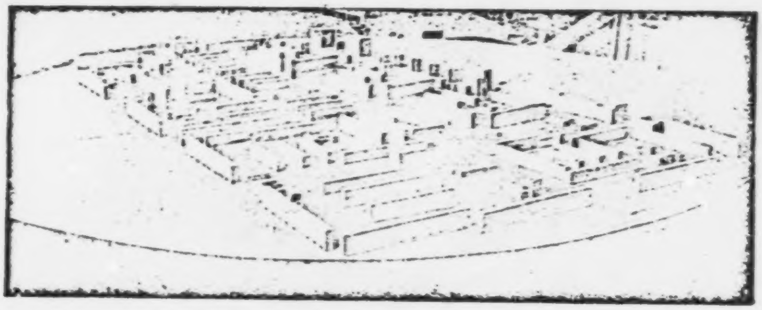

Fig. 8. Model of urban building system (second type).

At an increased turbulence of the forward flow ($\varepsilon_0 = 10\%$), the turbulence intensity above the second model increases sharply, reaching 80-100%, and the approximately rectilinear boundary separating the disturbed from the undisturbed region has a large inclination (up to 6-7°). As was shown by the analysis, the angle of inclination of the boundary depends on the relationship between the mean height of the irregularities $h_0$ of the earth's surface and the turbulence scale $L_t$, which is related to the turbulence intensity of the incoming flow.

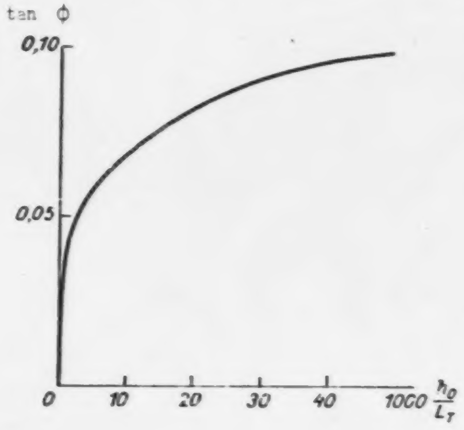

Fig. 9. Dependence of angle of inclination of boundary of turbulent disturbance on ratio of surface roughness to turbulence scale.

As the turbulence intensity of the forward flow or more exactly of the ratio $h_0/L_t$ increases, the angle of inclination of the boundary has a tendency to stabilize (Fig. 9). This fact may turn out to be very useful in the solution of certain problems related to the diffusion and determination of regions of disturbances above different ground obstacles.

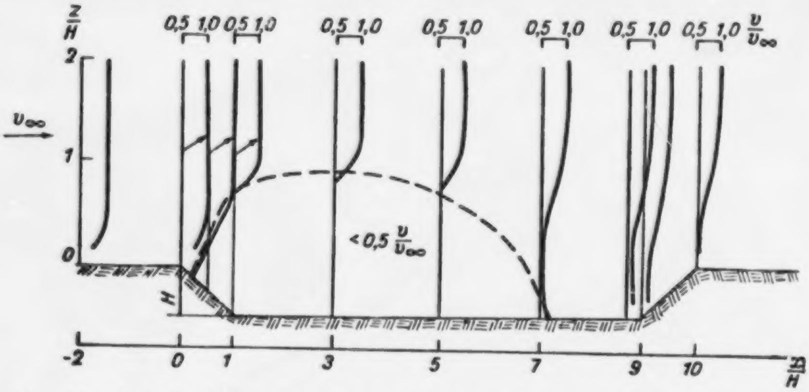

Fig. 10. Distribution of relative velocities in flow around trapezoidal depression.

Studies of the velocity distribution inside blocks with modern buildings showed the presence of zones with an increased velocity (with "straight-through blowing") and also stagnant zones and zones with a velocity directed against the wind direction. However, this information on the "nonaerodynamicity" of the urban building system studied is not the most important part. More important is the fact that the turbulence intensity of the forward flow (wind) substantially affects the velocities within the blocks. Special experiments showed that in this sense, for a part of the block, an increase of turbulence (up to $\varepsilon_0 = 5\%$) is equivalent in its effect to the erection in front of the "city" of a continuous wall (barrier) of a height equal to the mean double height of the houses in the block. These facts make it necessary to use particular caution in setting up and conducting experiments in wind tunnels with models and obstacles of complex shape and also in evaluating the results of known experiments. Particular attention should be given to the measurement of the initial turbulence of the incoming flow, to which the experimental results are referred.

Results of the study of a current above a depression are shown in Figs. 10 and 11, on condition that in the incoming flow $\varepsilon_0 = 0.2$. As is evident from an analysis of these figures, velocity and particularly turbulence disturbances are particularly sharp in character, owing to turbulent flows within the depression itself. However, at a distance (along the vertical) of only about 3-4 "depths" of the depression, the flow becomes practically normalized.

On the whole, wind tunnel studies of flow around models of a hill, urban building systems and other ground obstacles yielded data on the disturbance

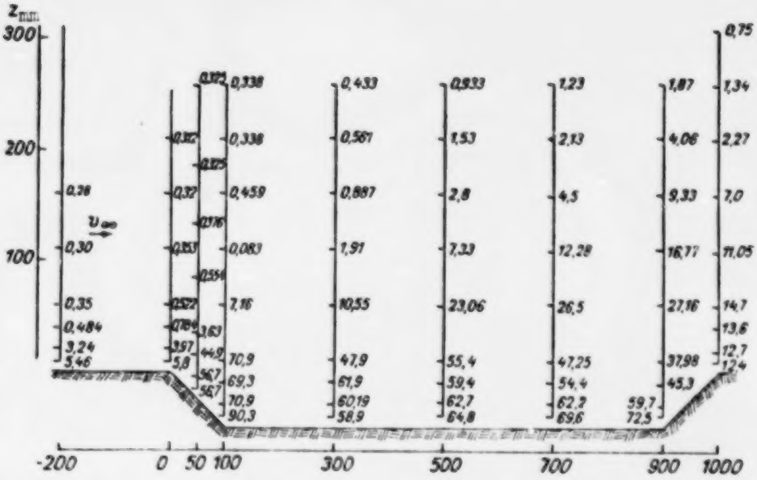

Fig. 11. Distribution of turbulence intensity in flow around trapezoidal depression.

of the flow above them. They led to the conclusion that the influence of Re and $\varepsilon$ numbers is small when the protruding superstructure is slight and smooth, and that $\varepsilon_0$ has a substantial influence in the case of complex obstacles. They also made it possible, by taking similarity into consideration, to evaluate more accurately the formulation and execution of experiments with ground obstacles and wind tunnels, this being very important for the solution of a number of meteorological problems. In further experiments it is desirable to carry out comparisons of wind tunnel experiments with measurements under natural conditions in order to establish more precise conditions of transition from the tunnel to nature for various ground obstacles.

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## THE INVESTIGATION OF INFLUENCE OF GROUND SURFACE ROUGHNESS ON AIR FLOW CHARACTERISTICS IN WIND TUNNEL*

The investigation of concentration field and air currents in the complex relief conditions can be fulfilled with the help of laboratory modelling and also on the basis of laboratory experiments and numerical investigations.

The Institute of Mechanics of Moscow State University and the Main Geophysical Observatory carry out the works on simulation of flow pattern over topographical features of the earth in wind tunnel. Substantial attention is paid to the questions connected with the effect of Reynolds number and air flow turbulence intensity on current pattern. The experiments are carried out in some wind tunnels under different upstream conditions (velocity and turbulization). The comparison with data obtained in natural conditions is carried out.

In the case, when characteristic turbulence scale is of order of the size of studied obstacle, the effect of upstream turbulence intensity is substantial. For all this, the character of the effect depends on the form of the body and considerably influences current pattern over complex obstacles. As a rule, the increase of intensity of turbulence leads to more monotonous velocity distribution and to the increase of turbulized zone.

The change of Reynolds number does not influence practically speaking on the whole current structure in rather large range, except the thin layer directly adjacent ot obstacle.

As a result of these investigations, velocity field and intensity of longitudinal turbulence component over flat hills with different slope and shape, hollows, three-dimensional hill, two types of residential buildings and some other obstacles were studied. The change of turbulence intensity in the region of hill model with a slope up to 16° is not very large.

A decrease of turbulence intensity is observed in the regions of flow convergence, i. e. in the front part of the hill, and more substantial increase is found in its back part. Velocity braking behind the hill with a slope of 12° reaches 50% from upstream velocity and includes the region equal to half the height of the model.

Disturbances brought into the flow by the hollow have especially sharp character, but the current is practically normalized already at the height equal to 3 ÷ 4 hollow "depths". Turbulence intensity over residential building model increases sharply. Eddy zone has rectilinear boundary with large slope up to 6—7°. The angle of slope of this boundary depends on ratio of mean building height and characteristic turbulence scale.

The obtained results and their comparison with observational data in natural conditions show that they are in good agreement.

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* Editor's note: The abstract is presented as given in English with the original Russian article.

# USE OF PARAMETERS OF EULERIAN TURBULENCE FOR ESTIMATES OF LAGRANGIAN CHARACTERISTICS

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From Glavnoe Upravlenie Gidrometeorologicheskoy Sluzhby Pri Sovete Ministrov SSSR. (Chief Administration of the Hydrometeorological Service Under the Council of Ministers of the USSR.) "Meteorologisheskie Aspekty Zagryazneniya Atmosfery". (Meteorological Aspects of Air Pollution.) Sbornik dokladov na mezhdunarodnom simpoziume v Leningrade - Iyul' 1968 g. (Reports delivered at the International Symposium in Leningrad - July 1968.) Pod redaktsiey d-ra fiz.-mat. nauk M. E. Berlyanda. (Edited by Prof. M. E. Berlyand.) Gidrometeorolgicheskoe izdatel'stvo, Leningrad, p. 162-178, (1971). (Hydrometeorological Publishing House, Leningrad, (1971).)

It is well known that the process of turbulent diffusion is determined by the turbulent characteristics of the velocity field. We will discuss the principal methods of determination of diffusion parameters in the lower atmospheric layer from the standpoint of the use of turbulent characteristics in such calculations. Major attention will be given to the possibility of using for this purpose turbulent characteristics that at the present time can be determined relatively simply by experimental means.

Two different approaches to the solution of turbulent diffusion problems may be indicated at the present time.

1. Use of a semiempirical equation. To calculate the concentrations of a passive impurity it is necessary to know in this case such parameters of the lower atmospheric layer as the coefficients of turbulent diffusion $k_x$, $k_y$ and $k_z$, and also the wind velocity in the layer under consideration. Of the above-enumerated coefficients of turbulent diffusion, the most accessible (from the standpoint of the possibilities of its practical determination) is $k_z$. For a weightless passive impurity, a measure of $k_z$ may be the turbulent viscosity coefficient $k_z$, defined by the known ratio

$$k_z = \frac{\tau_T}{\frac{\partial u}{\partial z}}, \qquad (1)$$

where $\tau_t$ is the tangential frictional stress and $\frac{\partial u}{\partial z}$ is the mean wind velocity gradient.

While the determination of $\frac{\partial u}{\partial z}$ is comparatively simple in the surface layer, its evaluation at heights greater than 50-100 m involves a large error. This is explained first of all by the difficulty of measuring small values of $\frac{\partial u}{\partial z}$.

As an illustration, we present data on the magnitude of mean wind velocity gradients obtained from results of two-year observations on the Obninsk meteorological mast of the Institute of Experimental Meteorology [11] (Table 1).

Table 1

Mean Vertical Wind Gradients According to Periods and Seasons

($\frac{\partial u}{\partial z}$ m/sec per 100 m)

| Layer, m | Time, hours | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 7 | 13 | 19 | 1 | 7 | 13 | 19 |
| | Winter | | | | Spring | | | |
| 0—100 | 6,2 | 6,0 | 5,4 | 5,9 | 6,4 | 5,2 | 5,6 | 6,6 |
| 100—200 | 1,0 | 1,7 | 1,3 | 1,1 | 1,5 | 1,2 | 0,5 | 1,3 |
| 200—300 | 0,0 | 0,2 | 0,4 | 0,6 | —0,1 | 0,0 | 0,5 | 0,5 |
| | Fall | | | | Summer | | | |
| 0—100 | 6,3 | 5,5 | 5,5 | 5,9 | 5,5 | 4,0 | 5,2 | 5,1 |
| 100—200 | 1,5 | 1,9 | 0,9 | 1,8 | 1,5 | 1,4 | 0,6 | 1,0 |
| 200—300 | 0,6 | 1,2 | 0,5 | 0,6 | 0,8 | 0,5 | 0,5 | 0,5 |

It follows from these data that the errors in the determination of $\frac{du}{dz}$ and hence, $k_z$ for heights greater than 100 m may reach several hundred percent with the existing accuracy of the measurements of $\frac{du}{dz}$.

It should be noted also that the determination of the tangential friction $\tau_t$ makes it necessary to use measuring devices that permit simultaneous measurement of two components, the longitudinal and the vertical components of the wind velocity.

The turbulent diffusion coefficients $k_x$ and $k_y$ for a boundary layer cannot be determined from a ratio analogous to (1). The procedure for determining these coefficients from the meteorological parameters of the lower atmospheric layer has not yet been described in the literature. As a rule, they are evaluated only from results of measurement of the turbulent diffusion itself. In theoretical calculations, various relationships that in many cases have no adequate physical justification are used in calculations of these quantities. Thus, an urgent problem is to develop a method of their determination on the basis of characteristics of the lower atmospheric layer.

2. Use of statistical theory of turbulent diffusion. To evaluate the distribution of an impurity concentration in the simplest case of a uniform

isotropic turbulent velocity field, it is necessary to know the structural function of the coordinates $\sigma^2$ as a function of time t and other parameters. This structural function is expressed via the velocity correlation function $R_L(\tau)$ in Lagrangian variables:

$$\sigma^2(t) = 2\int_0^t (t-\tau) R_L(\tau)\, d\tau. \tag{2}$$

Assuming that the distribution of the impurity particles obeys the normal law, by using $\sigma^2$ one can carry out the necessary calculations. Relation (2) was derived for homogeneous and isotropic turbulence. However, approximate methods of calculation may be proposed that may be used for an inhomogeneous and nonisotropic velocity field [2].

Thus, the use of statistical theory presupposes the knowledge of the velocity correlation function $R_L(\tau)$ and its dependence on stratification and other meteorological parameters. However, for the lower atmospheric layer, the character of the correlation function has been practically unstudied (with the exception of the relationships in the inertial interval). One can indicate an approximate procedure used by the authors of [5], based on the hypothesis of similarity of the Eulerian $R_E(\tau)$ and Lagrangian $R_L(\tau)$ velocity correlation functions:

$$R_E(\tau) = R_L(\beta\tau). \tag{3}$$

Although the dependence of the functions $R_E(\tau)$ and $R_L(\tau)$ on the time shift $\tau$ is generally different, this assumption makes it possible to carry out approximate calculations of $\sigma^2$ along different directions if the numerical value of the parameter $\beta$ is known. However, at the present time, the value of $\beta$ itself is known only with a rough approximation, which makes it impossible to obtain reliable data on $R_L(\tau)$. The difficulties of this approach are complicated even further by the fact that this procedure is not based on any physical hypotheses that would facilitate the finding of the dependence of $\beta$ on meteorological and turbulence parameters.

In addition to the methods enumerated above, mixed ones are also used, in which statistical theory and semiempirical equations are used simultaneously [9]. Thus, to describe diffusion in the vertical direction, a semiempirical diffusion equation is used, and in other directions the distribution is given by using Lagrangian representations. From the point of view under consideration, this method contains no new turbulence parameters other than those discussed above.

In this connection, theoretical and experimental studies were carried out at the Institute of Experimental Meteorology for the purpose of working out a method of computation [1, 2]. The latter is based on the use of similarity theory, the principles of which are given in the works of Batchelor [14] and

Obukhov and Monin [11].

We will begin the discussion with estimates of the turbulent diffusion coefficients. As we know, the turbulent diffusion coefficient k may be defined by the expression $k=\frac{1}{2}\frac{\partial\sigma^2}{\partial t}$.

Introducing the integral time scale $\tilde{\tau}_L$ of the Lagrangian velocity correlation function $R_L(\tau)$, and examining this quantity for each of the velocity components $\{v_i\}=\{u, v, w\}$, we obtain an estimate of the turbulent diffusion coefficients along different directions. For a sufficiently long time $\tau$, $\{k_i\}=\{k_x, k_y, k_z\}$ may be represented in the form

$$k_i=\overline{v_i^2}\tilde{\tau}_{Li}, \tag{4}$$

where $\overline{v_i^2}$ is the turbulent energy of the i-th velocity component.

It should be noted that expression (4) does not require the knowledge of wind velocity gradients or other mean values. However, expression (4) contains the time scale $\tilde{\tau}_{L_i}$, which in contrast to $\overline{v_i^2}$, requires a determination

from the standpoint of the possibilities of its measurement in the experiment. To evaluate this quantity, one can make use of dimensional theory considerations. From the standpoint of its physical meaning, $\tilde{\tau}_L$ represents the characteristic lifetime of energy-carrying turbulent inhomogeneities. If we know the total turbulent energy of a velocity component $\overline{v^2}$, and also that part of it which dissipates per unit time, $\varepsilon$ (i.e., the dissipation of turbulent energy), the characteristic lifetime $\tilde{\tau}_L$ should be given by the relation

$$\tilde{\tau}_{Li}=\frac{1}{\alpha}\frac{\overline{v_i^2}}{\varepsilon}, \tag{5}$$

where $\alpha$ is some numerical constant.

Like $\overline{v^2}$, the dissipation of turbulent energy $\varepsilon$ is a quantity accessible to measurements, and therefore relation (5) may be used to evaluate $\tau_{Li}$ from experimental data of Eulerian turbulence. Thus, by taking (5) into account, the turbulent diffusion coefficient $k_i$ may be evaluated by means of the relation

$$k_i=\frac{1}{\alpha}\frac{(\overline{v_i^2})^2}{\varepsilon}. \tag{6}$$

In order to be able to use formula (6) for practical estimates of $k_i$, it is necessary to refine the value of the numerical constant $\alpha$. To this end, we will compare the value of the turbulent viscosity coefficient $k_z \equiv k_3$, given by formula (1), with $k_3$, given by formula (6). This may be done on the basis of data on the best-studied part of the boundary layer - the atmospheric surface layer.

As we know, in a surface layer with indifferent stratification $k_z = \varkappa v_* z$, where $v_*$ is the dynamic velocity, and $\varkappa$ is von Kármán's constant. Substituting into formula (6) the expression for the dissipation of turbulent energy in the surface layer $\varepsilon = \frac{v_*}{\varkappa z}$, and also expressing the turbulent energy of the vertical component in terms of the dynamic velocity $\overline{w^2} = v_*^2$ [8], we obtain

$$k_z = \frac{1}{a} \varkappa v_* z,$$

which is in complete agreement with the expression given above for $k_z$ in the surface layer for the proportionality coefficient a = 1.

Because of a lack of experimental data for the atmospheric boundary layer, we are unable to draw a similar comparison for $k_z'$ and $k_3$, which would enable us to estimate the numerical value of $\alpha$. However, this may be done for the boundary layer on a flat plate, a layer that is similar in physical properties and that has been studied in a wind tunnel [10]. Figure 1 shows the ratio $\frac{k_3}{k_z'}$ (for cases of $\frac{\overline{u}}{v_*}$, equal to 0.04 and 0.045, where $\overline{u}$ is the velocity of undisturbed flow).

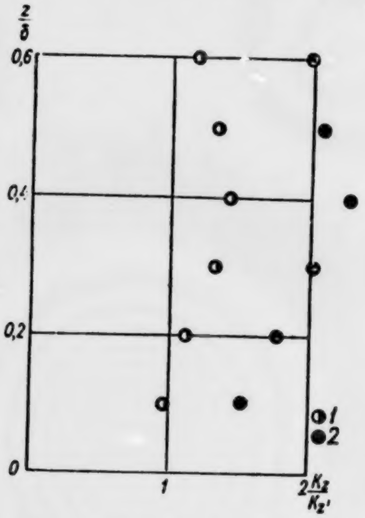

Fig. 1. Ratio of turbulent diffusion coefficient $k_z$ to turbulent viscosity coefficient $k_z'$ for boundary layer on flat plate.

1) $\frac{\overline{u}}{v_*} = 0{,}045$; 2) $\frac{\overline{u}}{v_*} = 0{,}04$.

As follows from the above estimates, the equality of $k_z'$ and $k_3$ makes it necessary that the constant entering into formula (6) be approximately equal to 0.5-1.0 when averaged out over the layer, this being in agreement with estimates of this constant in the surface layer. As shown by calculations of $\alpha$ based on other considerations, this quantity is also close to unity [2, 6, 7]. Thus, for the vertical component, the numerical coefficient $\alpha$ entering into expression (6) is close to unity. It may be expected that the numerical coefficients entering into the expression for the diffusion coefficients $k_x$ and $k_y$ are also close to unity.* With this assumption, expression (6) may be used for estimating the turbulent mixing coefficients $k_x$, $k_y$ and $k_z$.

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* Generally speaking, it is possible that this constant may be slightly different for the coefficients k along different directions. However, this possibility will not be considered at this stage.

The representation of $\overline{v_i^2}$ and $\varepsilon$ as functions of stratification makes it possible in turn to find the dependence of $k_x$, $k_y$ and $k_z$ on the stratification.

Using relation (6), one can estimate the degree of anisotropy of turbulent mixing along different directions in the lower atmosphere. We will use for this purpose data on the mean turbulent energy $\overline{v_i^2}$, whose values for the lower layer of the atmosphere are known (in particular, for the surface layer).

The magnitude of dissipation of turbulent energy entering into (6) is the same for the coefficients along all the directions. As follows from the data given in [8], the ratio $\sqrt{\overline{u^2}}:\sqrt{\overline{v^2}}:\sqrt{\overline{w^2}}$ is approximately proportional to 2.4:2:1. It follows that the turbulent diffusion coefficients of (6) have to stand approximately in the ratio 30:15:1. This indicates a significant anisotropy of mixing in the atmospheric boundary layer along different directions. An important fact is that $k_x$ and $k_y$ surpass $k_z$ by more than one order of magnitude. This fact is in accord with other estimates.

We will now consider the application of similarity theory to the evaluation of the structural function of the coordinates $\sigma^2$. In Batchelor's papers, such estimates are made for the inertial range for the relative diffusion of a pair of particles [3]. If this theory is applied to a Lagrangian acceleration field j(t), the acceleration spectrum $S_j(f)$ is independent of frequency in this case: $S_j(f)=c_1\varepsilon$, and the correlation function for the inertial range will have the form [4]

$$R_L(\tau)=\overline{v^2}-c_1\varepsilon\tau=\overline{v^2}\left(1-\frac{\tau}{\tau_L}\right), \tag{7}$$

where $\tau=\frac{\overline{v^2}}{c_1\varepsilon}$, and $c_1$ is a numerical constant close to 0.7*.

Using (7) and (2), one can estimate the variance of the coordinates $\sigma^2$ also by using the parameters of Eulerian turbulence $\overline{v^2}$ and $\varepsilon$.

Let us consider certain experimental data on direct measurements of the Legrangian velocity correlation function in the lower atmosphere. These results were obtained in [15], where constant-level balloons (whose trajectories were recorded by means of radar) were used to evaluate $R_L(\tau)$. The results obtained show that in the lower atmosphere at heights of 100-300 m, the correlation function $R_L(\tau)$ is close to linear for time scales of 35 minutes (Fig. 2).

However, from a practical standpoint it is more convenient to check, not the expression itself for the velocity correlation function (7), but its consequences.

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* Instead of relation (7), an extrapolation formula for $R_L(\tau)$ may be proposed in the form of an exponent [2]. Expression (7), which applies in the inertial range, will in this case be made up of the first terms of the expansion of the exponential correlation function.

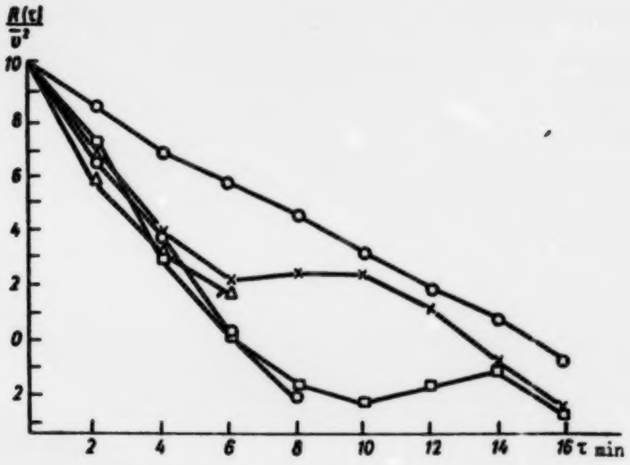

Fig. 2. Experimental data on the Lagrangian velocity correlation function.

Thus, by substituting expression (7) into (2), we find that the structural function of the coordinates for one particle has the following form:

$$\sigma_1^2(\tau) = \overline{v^2}\tau^2 - \frac{c_1}{3}\varepsilon\tau^3. \tag{8}$$

If the plume from a point source is treated as complex motion consisting of the motion of its instantaneous center of gravity and the motion relative to this center, then the structural function describing the change of the instantaneous center of gravity will be

$$\sigma_0^2(\tau) = \overline{v^2}\tau^2 - \frac{c_1 + 0.7}{3}\varepsilon\tau^3. \tag{9}$$

Since expressions (8) and (9) are a consequence of the fact that the correlation function $R_L(\tau)$ has the form (7) and is determined by the parameters $\overline{v^2}$ and $\varepsilon$, their agreement with experimental results should indicate that the form of the correlation function and of the parameters determining it is correct.

A check of relations (8) and (9) was made at the Institute of Experimental Meteorology. The results obtained are given in [4]. Transverse diffusion from a point source located at a height of 100 m was studied. Simultaneously, the turbulent characteristics $\overline{v^2}$ and $\varepsilon$ were measured with the aid of the measuring system of a high-level meteorological mast. Comparison of $\sigma_z^2$ values calculated by using the parameters of the turbulent velocity field $\overline{v^2}$ and $\varepsilon$ and also measured directly in observations of smoke plumes indicates satisfactory agreement to within a time $\tau_L$ of the order of 500-800 sec (spatial scale of 1500-2000 m).

A check of relation (9), made in similar fashion, showed that there is also satisfactory agreement between the theoretical estimates and the experimental data. It should be noted that because of the difficulty of selecting stationary conditions in conducting the experiment, a somewhat greater scatter is observed in this case.

To illustrate the degree of agreement between the two methods of estimating $\sigma^2$, we reproduce the data on $\overline{v^2}$ and $\varepsilon$ given in [4], obtained from direct measurements and by estimating these parameters from a smoke plume in the inertial interval (Table 2).

Table 2

Values of and $\sqrt{\overline{v^2}}$, Obtained from Direct Measurements with $\varepsilon_g$ and $\sqrt{\overline{v_g^2}}$ Obtained by Evaluation from a Smoke Plume.

| Experiment | $\varepsilon$ cm$^2$/sec$^3$ | $\varepsilon_g$ cm$^2$/sec$^3$ | $\sqrt{\overline{v^2}}$ m/sec | $\sqrt{\overline{v_g^2}}$ m/sec |
|---|---|---|---|---|
| 1 | 0,65 | 1,0 | 0,18 | 0,22 |
| 2 | 13,0 | 20,0 | 0,66 | 0,64 |
| 3 | 2,2 | 4,0 | 0,24 | 0,26 |
| 4 | 0,4 | 0,5 | 0,23 | 0,25 |
| 5 | 4,8 | 5,8 | 0,39 | 0,31 |

Thus the proposed method may be considered to give a satisfactory agreement with results of experimental measurements and shows that it may be used as the basis for a method of calculating the parameters of turbulent diffusion. Its application to the case of inhomogeneous velocity fields naturally contains certain errors, but, as shown by the data of Table 1, they are insignificant for a height of 100 m in relation to transverse diffusion.

Let us find the relationship between the method of calculation discussed in [5] in the approximation of similarity of the Lagrangian and Eulerian correlation functions (cf. formula (3)) and the above-discussed results of similarity theory. Such a relationship may be established fairly simply for the range of turbulent inhomogeneities best studied to date, i.e., the inertial range. Let us consider for this range the relationship between the Lagrangian and Eulerian time scales.

As we know, the Eulerian velocity correlation function in the inertial range has the form

$$R_E(\tau) = \overline{v^2} - c\varepsilon^{2/3}(\overline{u}\tau)^{2/3}, \qquad (10)$$

where $\overline{u}$ is the mean velocity and c is a numerical constant (practically equal to unity for the longitudinal correlation function). We take the quantity $\tau_1$ from (5) introduced earlier and use it to express $R_E(\tau)$ from (10):

$$R_E(\tau)=\overline{v}^2\left[1-A\left(\frac{\tau}{\tau_L}\right)^{2/3}\right], \tag{11}$$

where

$$A=\frac{c}{c_1^{2/3}}\left(\frac{\sqrt{\overline{v^2}}}{\overline{u}}\right)^{-2/3}$$

and $c_1$ is a numerical constant entering into expression (7).

The expression for the coefficient A entering into (11) shows that $A \gg 1$ (since $\frac{\sqrt{\overline{v^2}}}{\overline{u}} \ll 1$). This indicates a slower decrease of the Lagrangian correlation function to zero as compared with the Eulerian function.

We find the Eulerian $\tau_{0E}$ and Lagrangian $\tau_{0L}$ turbulence scales by defining them as the time interval corresponding to a twofold decrease of the normalized correlation function:

$$\frac{R_L(\tau_{0L})}{\overline{v^2}}=0,5;\quad \frac{R_E(\tau_{0E})}{\overline{v^2}}=0,5. \tag{12}$$

It is assumed that in such a decrease of the correlation function, we do not overstep the boundaries of the inertial range in either case.

Use of conditions (12) together with expressions (11) and (7) (using numerical values of the constants $c_1 = 0.7$ and $c = 1$) leads to the following time scales:

$$\tau_{0E} \simeq 0,25\tau_L\frac{\sqrt{\overline{v^2}}}{\overline{u}}; \tag{13}$$

$$\tau_{0L} \simeq 0,5\tau_L. \tag{14}$$

Thus, $\beta$, which represents the ratio of the time scales, will be equal to

$$\beta=\frac{\tau_{0L}}{\tau_{0E}}=2\left(\frac{\sqrt{\overline{v^2}}}{\overline{u}}\right)^{-1}. \tag{15}$$

Expression (15) indicates a possible dependence of $\beta$ on the stratification: in the presence of unstable stratification, it should be less than in the presence of indifferent stratification or inversion.

Let us consider some operational aspects connected with the experimental determination of the turbulent energy $\overline{v^2}$ and its dissipation $\varepsilon$ in the lower atmosphere. The procedure for determining the turbulent energy of the wind velocity components $\overline{v^2}$ is known. In the surface layer, its evaluation may be made by using the similarity theory [13], for which it suffices to know the mean profiles of wind velocity and temperature. The characteristic feature of its measurement at heights of 50-100 m lies in the fact that it may be measured with satisfactory precision by means of a fairly coarse gauge, for example, one having a time constant of 2-5 sec (excluding stable stratification). The Obninsk meteorological mast uses propeller gauges (1-sec lag) and also bivanes (1-4-sec lag) for this purpose. Estimates show that the error in the determination of turbulent energy due to limitation of the transmission band by the lag of the gauges does not exceed 5%.

Let us now consider certain questions connected with the determination of the dissipation of turbulent energy $\varepsilon$. Most widely used for the determination of $\varepsilon$ at the present time are the regularities of the inertial range, where the structural function of the velocity field $D(\tau)$ has the form

$$D(\tau)=\left[\overline{u(t)-u(t+\tau)}\right]^2=2c\varepsilon^{2/3}(\bar{u}\tau)^{2/3}. \qquad (16)$$

Here 2c is a numerical constant equal to 1.95 for the longitudinal component. The spectral density is described by the expression

$$S(w)=\hat{c}\,\bar{u}^{-2/3}\varepsilon^{2/3}w^{-5/3}, \qquad (17)$$

where $\hat{c}\approx 0{,}5c$.

Formulas (16) and (17) are equivalent from the standpoint of the possibilities of determination of $\varepsilon$. However, the determination of $\varepsilon$ from structural function (16) has certain advantages. First, this is due to a smaller quantity of arithmetic operations, since the determination of $S(w)$ makes it necessary also to carry out a transformation of $D(\tau)$ or to filter $u(t)$, which is a very laborious operation. Secondly, the following fact should be pointed out. As a rule, in measurements of the fluctuation components of the wind velocity, it is necessary to use gauges having a certain lag. If the impulsive admittance function $h(t)$ of the measuring system is in the exponential form $h(t)=e^{\frac{-t}{\tau_0}}$, где $\tau_0$ where $\tau_0$ is the time constant, then instead of expressions (16) and (17) for $u(t)$ measured with the aid of these gauges, other relations will hold:

(a) for the structural function

$$\tilde{D}(\tau)\simeq 2c\varepsilon^{2/3}\bar{u}^{2/3}\left(\tau^{2/3}-\tau_0^{2/3}\cdot 0.9\right); \qquad (16a)$$

(b) for the spectral density

$$\tilde{S}(w)=\hat{c}\,\bar{u}^{-2/3}\varepsilon^{2/3}\frac{w^{-5/3}}{(w\tau_0)^2+1}. \qquad (17a)$$

The expression for the structural function is approximate and applies starting with time $\tau \geqslant 3\tau_0$.

Let us note that if in the determination of spectral density (17a) the distortions due to lag of the gauge are different at different frequencies, then for the structural function the influence of the lag amounts only to the appearance of the constant additional term $\sim 0{,}9\tau_0^{2/3}$, which is independent of the shift $\tau$. It is easy to show that the dissipation of turbulent energy $\varepsilon$ calculated from expression (16a) will be determined by a relation that is independent of the time constant $\tau_0$:

$$\varepsilon = \frac{0{,}37}{\bar{u}}\left[\frac{\Delta D(\tau)}{\tau_2^{2/3} - \tau_1^{2/3}}\right]^{3/2}, \tag{18}$$

where $\Delta D(\tau)$ is the difference in values of the structural function at times $\tau_2$ and $\tau_1$, lying in the inertial range, and satisfying the condition $\tau_2, \tau_1 \gg 3\tau_0$.

When the time constant of the gauge is known only approximately, and also when the time constant itself is a function of the wind velocity (for example, for propeller and cup gauge), and therefore the introduction of a correction into the expression for $S(w)$ is considerably complicated, the most convenient method of determining $\varepsilon$ is to evaluate it from the structural function (18). The method given above is now being used on the Obninsk high-level meteorological mast. It makes it possible to evaluate $\varepsilon$, not with special quick-response gauges (hot-wire anemometer, acoustic anemometer), but with commercial M-49 propeller gauges used by meteorological networks.

Let us examine some experimental data on turbulent characteristics, obtained in the lower 300-meter atmospheric layer with the aid of the measuring system of the high-level meteorological mast of the Institute of Experimental Meteorology (Obninsk). The initial turbulent characteristic used for estimates of diffusion parameters were values of the turbulent energy $\overline{v_i^2}$ and its dissipation $\varepsilon$. We will give the experimental data on profiles of these characteristics in the lower 300-meter layer (the measured values of $\overline{v_i^2}$ pertain to the longitudinal component of the wind velocity $\overline{u^2}$). Each of the profiles of $\overline{u^2}$ and $\varepsilon$ shown in Fig. 3 was obtained by averaging over 5-7 separate series of observations, each lasting 30 minutes, pertaining to lower-layer conditions similar in stratification. The Monin-Obukhov parameter was used to estimate the stratification of the atmosphere [13]:

$$L = -\frac{v_*^3 c_p \rho}{\frac{g}{T} Q \varkappa}, \tag{19}$$

where g is the acceleration due to gravity, T is the mean temperature, $c_p$ is the heat capacity at constant pressure, $\rho$ is the air density, Q is the turbulent heat flow, and $\kappa$ is von Kármán's constant.

The values given in Fig. 3 were determined as the mean value $\bar{L}$ for the given group of profiles. As shown by the results obtained, a monotonic

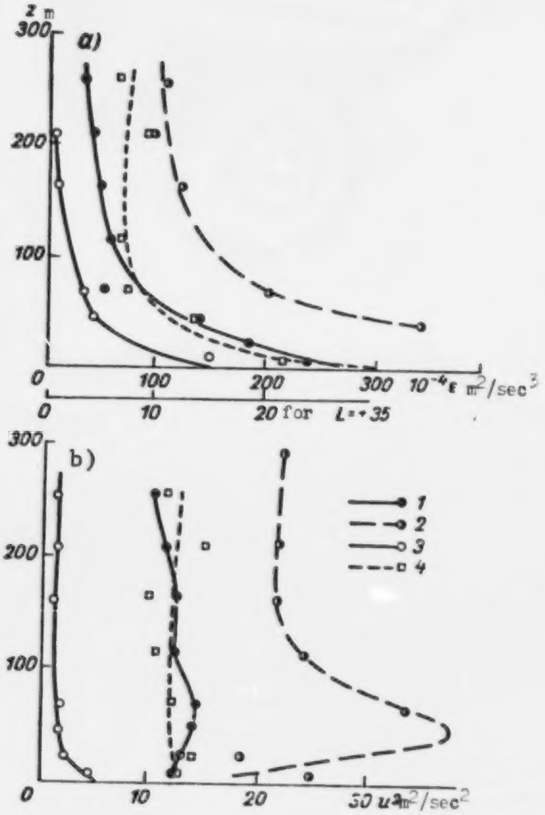

Fig. 3. Profiles of turbulent energy $\overline{u^2}$ (a) and its dissipation ε (b) for different stratifications.
1) h = -135 m, 2) h = -24 m, 3) L = +35 m, 4) L = -6m.

dependence of $\overline{u^2}$ and ε on the stratification is observed: for a stable stratification ($\overline{L}$ = +35), the dissipation and the turbulent energy are substantially less than for an indifferent and unstable stratification. Attention is drawn to the fact that the dimensional values of $\overline{u^2}$ and ε in the presence of a marked instability ($\overline{L}$ = -6) and slight instability ($\overline{L}$ = -100) are close to each other. This is because in the presence of a strong instability, the mean wind velocity is low, and the group $\overline{L}$ = -100 corresponds to a high wind velocity. Although the causes of generation which make the chief contribution to the turbulent energy and dissipation are different in these states, their absolute values are close to each other. In dimensionless coordinates they should differ from each other.

The values of $\overline{u^2}$ and ε in the presence of an instability occupying an intermediate position ($\overline{L}$ = -24), turn out to be maximum in absolute value.

This is due to the fact that the series studied are characterized by a higher wind velocity (dynamic turbulence), and also an appreciable inflow of heat.

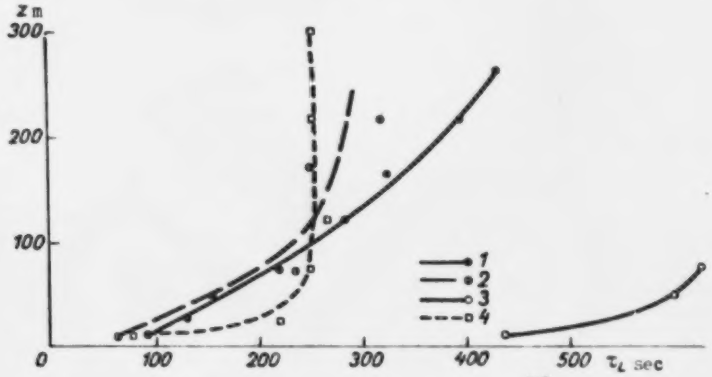

Fig. 4. Estimates of Lagrangian time scale $\tau = \frac{\overrightarrow{v^2}}{0{,}7\varepsilon}$ for different stratifications. For notation see Fig. 3.

The indicated experimental data on values of the longitudinal component of turbulent energy $\overrightarrow{u^2}$ and $\varepsilon$ were used to calculate the parameters of turbulent diffusion in accordance with the relations given above. Figure 4 shows data on an estimate of the Lagrangian characteristic time scale $\tau_L$ given by formula (5) with constant c = 0.7. They show that the values of $\tau_L$ are similar for different groups pertaining to a weak and strong instability. For heights of 100-300 m, $\tau_L \approx 5$ min, which is in good agreement with results of direct measurements shown in Fig. 2, and also in [4]. In the presence of an inversion, $\tau_L$ is slightly larger, which also agrees with the experimental estimates given in the above-mentioned paper.

Let us consider one more quantity, which is determined by the Lagrangian time and constitutes an estimate of the distance along the flow over which the principal process of decay of energy-carrying eddies takes place. This parameter is given by the relation $\lambda = \bar{u}\tau_L$. In contrast to $\tau_L$, $\lambda_L$ depends substantially on the stratification (Fig. 5). The estimates obtained show that this distance changes considerably with a change in the degree of instability of the lower atmosphere: $\lambda = 1.5$ km for $\overline{L} = -6$ and $\lambda = 6$-$8$ km for $\overline{L} = -100$.

We will estimate another important characteristic in calculations of turbulent diffusion parameters, i.e., the coefficient of turbulent mixing, by using formula (6) and a = 0.7. Results of calculations of $k_x = \frac{\overline{v}^4}{0{,}7\varepsilon}$ m$^2$/sec are given in Fig. 6.

Experimental data on $k_x$ values are not given in the literature, and for this reason the numerical $k_x$ values obtained cannot be compared with results of estimates by other methods. Use may be made only of the fact that $k_x : k_z = 30 : 1$ for an indifferent stratification. For $k_z$ we than obtain $k_z \approx 10^5$ cm$^2$/sec, which in order of magnitude agrees well with estimates obtained by other methods for the lower atmosphere [14].

In conclusion, we will cite the estimate of still another parameter, $\beta$, calculated in accordance with formula (15) (Fig. 7). From the results cited above it follows that $\beta$ should depend substantially on the stratification: $\beta \gtrsim 5$ for an unstable stratification and $\beta \gtrsim 20$ for a slight (close to indifferent) instability. As was shown by an estimate of the numerical constants, the values cited not only give a close enough description of the range of scales which enters into the inertial range, but can also be used to carry out the appropriate methodical treatment for estimates in the entire spectral range.

The proposed method of approaching the evaluation of turbulent diffusion parameters in the lower layer of the atmosphere is very promising. It contains no additional constants other than those used in the theory of turbulence and, in contrast to some other methods, permits a sufficiently detailed consideration of the dependence of the diffusion parameter on stratification. Although the method is approximate in principle, nevertheless in view of the fact that the accuracy required for solving practical problems is also relatively low, it is fully applicable to specific calculations. Its development was started relatively recently and it is important to bring it to the attention of researchers.

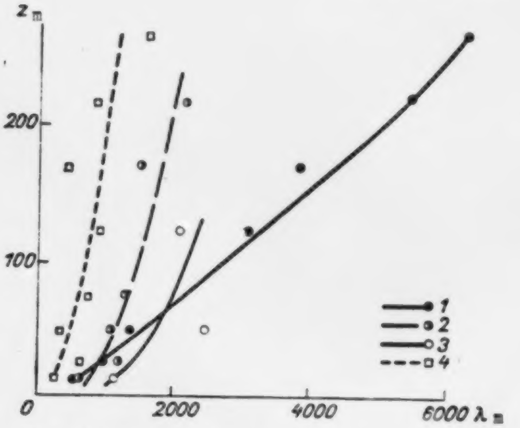

Fig. 5. Estimate of Lagrangian space scale $\lambda_L$ for different stratifications. For notation see Fig. 3.

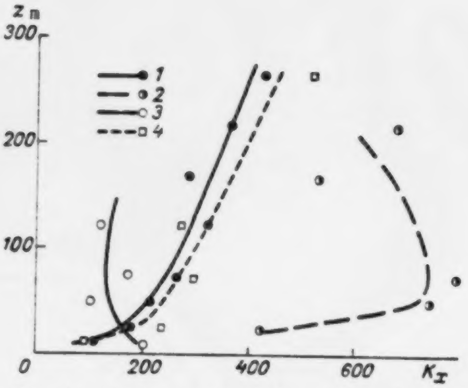

Fig. 6. Estimate of turbulent diffusion coefficient $k_x$ for different stratifications. For notation see Fig. 3.

Further development of this method should include an experimental determination of the correlation functions in Lagrangian variables for large shifts, and also a study of their dependence on stratification. Another important objective is to refine the constants entering into the above relations, and to allow for the influence of anisotropy and inhomogeneity of the lower atmosphere on the statistical characteristics. The development of this method will undoubtedly result in an accumulation of experimental data and will promote the creation of a theory of inhomogeneous and nonisotropic turbulence in Lagrange variables.

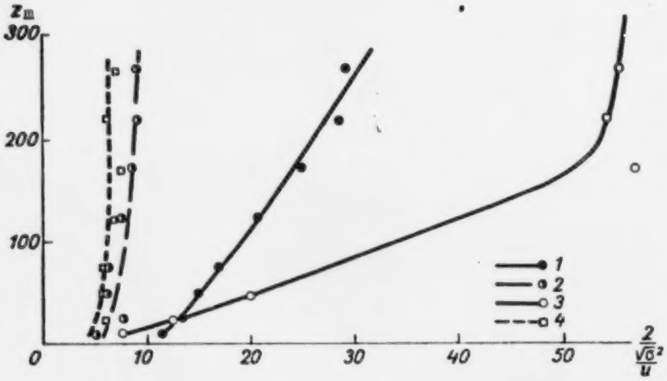

Fig. 7. Estimate of the parameter $\zeta = \frac{\tau_{OL}}{\tau_{OE}}$.

For notation, see Fig. 3.

The creation of such a theory will promote the solution of a large number of problems currently facing researchers in turbulent diffusion.

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*V. N. IVANOV*

## THE UTILIZATION OF EULERIAN TURBULENCE PARAMETERS FOR ESTIMATION OF LAGRANGIAN CHARACTERISTIC*

Evaluation method of Lagrangian turbulence characteristics necessary for pollutant diffusion calculation based on similarity theory is suggested and the Eulerian turbulence parameters are used. Though this method is approximate, the calculations of specific cases are carried out with exactness sufficient for practice. Calculations done on materials of special observations at the 300m mast of the Institute of Experimental Meteorology showed possibility of detailed calculation of thermal stratification effect on turbulent diffusion parameters. Vertical profiles of Lagrangian characteristic values of time and length, dissipation of turbulent energy, horizontal components of turbulent diffusion coefficient for different stratification conditions are obtained.

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*Editor's note: The abstract is presented as given in English with the original Russian article.

# METHOD OF EVALUATING ATMOSPHERIC DIFFUSION FROM TURBULENT CHARACTERISTICS

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From Glavnoe Upravlenie Gidrometeorologicheskoy Sluzhby Pri Sovete Ministrov SSSR. (Chief Administration of the Hydrometeorological Service Under the Council of Ministers of the USSR.) "Meteorologisheskie Aspekty Zagryazneniya Atmosfery". (Meteorological Aspects of Air Pollution.) Sbornik dokladov na mezhdunarodnom simpoziume v Leningrade - Iyul' 1968 g. (Reports delivered at the International Symposium in Leningrad - July 1968.) Pod redaktsiey d-ra fiz.-mat. nauk M. E. Berlyanda. (Edited by Prof. M. E. Berlyand.) Gidrometeorolgicheskoe izdatel'stvo, Leningrad, p. 179-193, (1971). (Hydrometeorological Publishing House, Leningrad, (1971).)

## 1. General Principles

The diffusion of a passive impurity in the atmosphere is determined by the mixing properties of the turbulent atmosphere and hence may be calculated from atmospheric characteristics of turbulence. The statistical method makes it possible to calculate the diffusion characteristics directly from the turbulent characteristics, without using the diffusion equation. At the same time, it makes it possible to introduce clarity into the problem of magnitude of coefficients of turbulent diffusion. In particular, it enables one to determine under what conditions they may be considered constant and in what cases they change with the duration of diffusion, and, in the presence of wind, with the distance from the source (for example, in the known schemes of Sutton, Bosanquet and Pierson [17]). A few examples of such treatment of certain problems are analyzed below.

Let us recall the basic initial assumptions of the method. We consider a smoke plume from the stack of an industrial enterprise (in the case of absence of thermal ascent) in the way we observe it (Fig. 1). As a rule, this plume expands with the distance from the stack, and its axis continually changes its position in space. An instantaneous plume may be treated as a collection of an infinite number of individual puffs successively emitted by a stationary source and carried by the mean wind, and a statistical model of a stationary plume is obtained by superimposing an infinite number of such instantaneous plumes (a similar scheme was first discussed by Gifford [4] and later by Ivanov and Stratonovich [7]). The motion of individual puffs consists of the dispersion of the puff relative to its instantaneous center ($\sigma_1$) and random wandering of the centers ($\sigma_2$), causing the sinuosity of the visible plume. This pattern is observed along the vertical direction as well as the horizontal direction perpendicular to the wind.

Let the dimensions of an instantaneous puff be $\delta$, and the dimension of the stationary puff (plume) formed by the superposition of instantaneous ones, $2\sigma_1$. Both the puff and the plume consist of an infinitely large number of particles whose coordinates will be denoted by $y_i(\tau)$, where $\tau$ is the time and *i* the particle number. The coordinate of their center of gravity at every instant of time (average coordinate with respect to the number of particles) will be denoted by $y_0(\tau)$, and the coordinate of the initial center of gravity, by $y_0 = y_0(0)$. In this case, the variance of the coordinates of the particles relative to the initial center of gravity

$$\sigma_1^2(\tau) = \langle [y_i(\tau) - y_0]^2 \rangle \qquad (1)$$

represents the square of the half-width of the stationary plume; the relative dispersion of two particles

$$\delta_2^2(\tau) = \langle [y_i(\tau) - y_j(\tau)]^2 \rangle \qquad (2)$$

is the square of the width of the instantaneous plume (or individual puff).

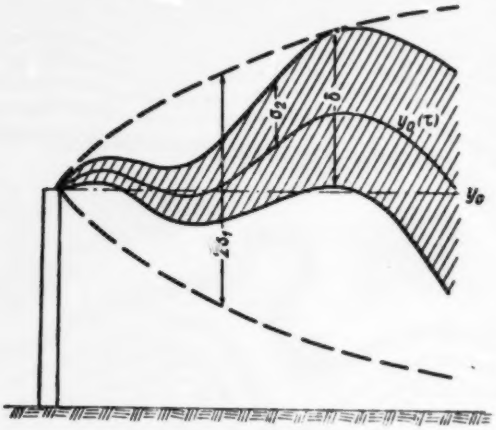

Fig. 1. Diagram of formation of smoke plume from a continually acting source.

We also determine the dispersion of the coordinates of the particles relative to their instantaneous center of gravity

$$\sigma_0^2(\tau) = \langle [y_i(\tau) - y_0]^2 \rangle \qquad (3)$$

and the dispersion of the center of gravity coordinates

$$\sigma_c^2(\tau) = \langle [y_0(\tau) - y_0]^2 \rangle. \qquad (4)$$

The angle brackets signify averaging over the statistical ensemble of the realization of the plume.

It is known [4, 7, 17] that the following relationship holds:

$$\sigma_1^2(\tau) - \sigma_c^2(\tau) = \sigma_2^2(\tau) = \frac{\delta^2(\tau)}{2}, \qquad (5)$$

which signifies that the dispersion of a puff relative to its instantaneous center and the wandering of the centers are independent, and in sum, their dispersions amount to the square of the half-width of the stationary plume.

The quantities entering into relation (5) are expressed via Lagrangian velocity correlation functions of one particle and a pair of particles. For one particle

$$R_i(\tau', \tau'') = \langle v_i(\tau') v_i(\tau'')\rangle; \tag{6}$$

the dispersion of one particle is determined from Taylor's formula

$$\sigma^2(\tau) = \int_0^{\tau}\int_0^{\tau} R_i(\tau', \tau'')\, d\tau'\, d\tau''. \tag{7}$$

The velocity correlation function of a pair of particles amounts to

$$R_{ij}(\tau', \tau'', r_0) = \langle v_i(\tau') v_j(\tau'')\rangle. \tag{8}$$

Here $v_i(\tau')$ is the Lagrangian velocity of the $i$-th particle at time $\tau'$, and $r_0$ is the initial distance between the $i$-th and $j$-th particles.

The dispersion of an instantaneous puff is determined by the combination of these two correlation functions

$$\tilde{\sigma}^2(\tau) = 2\int_0^{\tau}\int_0^{\tau} R_i(\tau', \tau'')\, d\tau'\, d\tau'' - 2\int_0^{\tau}\int_0^{\tau} R_{ij}(\tau', \tau'', r_0)\, d\tau'\, d\tau''. \tag{9}$$

The concrete form of the Lagrangian velocity correlation function of one particle is well-known in the inertial range, where this function depends linearly on the correlation interval $|\tau' - \tau''| = \tau$ and is determined by two quantities, the root-mean-square velocity fluctuation $\langle v^2\rangle$ and the Lagrangian scale $\tau_L$. This function is frequently approximated by means of an exponential function [15], which upon a series expansion for small r's gives a qualitatively correct dependence in the inertial region

$$\langle v_i(\tau') v_i(\tau'')\rangle = \langle v^2\rangle e^{-\frac{\tau}{\tau_L}}. \tag{10}$$

$(\tau = |\tau'' - \tau'|)$. This leads to the expression

$$\sigma_1^2(\tau) = 2\langle v^2\rangle \tau_L^2 \left(\frac{\tau}{\tau_L} + e^{-\frac{\tau}{\tau_L}} - 1\right). \tag{11}$$

In [10], using a generalization of the law of damping of equilibrium fluctuations and the method of random forces, both formula (10) and an expression for the correlation function of relative velocities of a pair of particles were obtained; for $\tau'' > \tau'$

$$\langle |v_i(\tau') - v_j(\tau')|\, |v_i(\tau'') - v_j(\tau'')| \rangle = \\ = 4\langle v^2 \rangle e^{-\frac{\tau''}{\tau_L}} \operatorname{sh} \frac{\tau'}{\tau_L} + D(r_0) e^{-\frac{\tau' + \tau''}{\tau_L}}. \tag{12}$$

Here $D(r_0)$ is the Eulerian spatial structural function of velocities, where $r_0$ is the initial distance between the particles. Hence, using the relation

$$\langle |v_i(\tau') - v_j(\tau')|\, |v_i(\tau'') - v_j(\tau'')| \rangle = \\ = 2\langle v_i(\tau') v_i(\tau'') \rangle - 2\langle v_i(\tau') v_j(\tau'') \rangle, \tag{13}$$

one can readily obtain the correlation function of two particles. For the inertial range, the structural function of two particles $\langle [v_i(\tau')\, v_j(\tau'')]^2 \rangle$ was obtained in [15] in implicit form. The paper [10] also gives an expression for the correlation function of the coordinates of a pair of particles in the case where this function no longer depends on the initial distance between the particles:

$$\frac{\delta^2}{2} = 2\langle v^2 \rangle \tau_L^2 \left[ \frac{\tau}{\tau_L} - \frac{3}{2} - \frac{1}{2} e^{-\frac{2\tau}{\tau_L}} + 2e^{-\frac{\tau}{\tau_L}} \right], \tag{14}$$

whence correspondingly

$$\sigma_0^2(\tau) = 2\langle v^2 \rangle \tau_L^2 \left[ \frac{1}{2} - e^{-\frac{\tau}{\tau_L}} + \frac{1}{2} e^{-\frac{2\tau}{\tau_L}} \right]. \tag{15}$$

If there is a constant drift at the mean wind velocity U, then, making the substitution $x = U_\tau$ in formulas (11), (14) and (15), one can obtain the dependence of $\sigma_1^2$, $\sigma_2^2$ and $\sigma_0^2$ on the distance to the source. As we know (as was found by Batchelor [7, 17] from similarity considerations), for small $\tau$'s, $\sigma_1$ and $\sigma_0$ change linearly with time $\tau$, and $\sigma_2$ is proportional to $\tau^{3}/_{2}$.

When the coordinate distribution function is Gaussian, a certain relation $k = \frac{1}{2} \frac{d\sigma^2}{d\tau}$, exists between $\sigma^2$ and the turbulent diffusion coefficient, whence

$$k_1 = k_0 \left( 1 - e^{-\frac{\tau}{\tau_L}} \right), \\ k_2 = k_0 \left( 1 + e^{-\frac{2\tau}{\tau_L}} - 2e^{-\frac{\tau}{\tau_L}} \right), \tag{16}$$

where $k_0 = \langle v^2 \rangle \tau_L$.

According to [2, 8, 10]

$$\tau_L = \frac{\langle v^2 \rangle}{c_1 \varepsilon},$$

where $\varepsilon$ is the dissipation of energy and $c_1$ is a dimensionless constant. Thus, having the measurement data for $\langle v^2 \rangle$ and $\varepsilon$, one can calculate both $k_o$ and $\tau_L$, and also, if the mean drift velocity (wind velocity) is known, the scale along the wind direction $x_L = \frac{\langle v^2 \rangle U}{c_1 \varepsilon}$. The formulas cited make it possible to evaluate this range of distances and the time during which the k values should depend on the time (or distances) and where they may be assumed constant:

for $\tau \ll \tau_L$ or $x \ll x_L$

$$k = \langle v^2 \rangle \tau = \langle v^2 \rangle \frac{x}{U},$$

$$\sigma_1^2 = \langle v^2 \rangle \tau^2 = \langle v^2 \rangle \frac{x^2}{U^2};$$

for $t \to \infty$

$$\sigma_2^2 \to \sigma_1^2 \to 2k_0\tau.$$

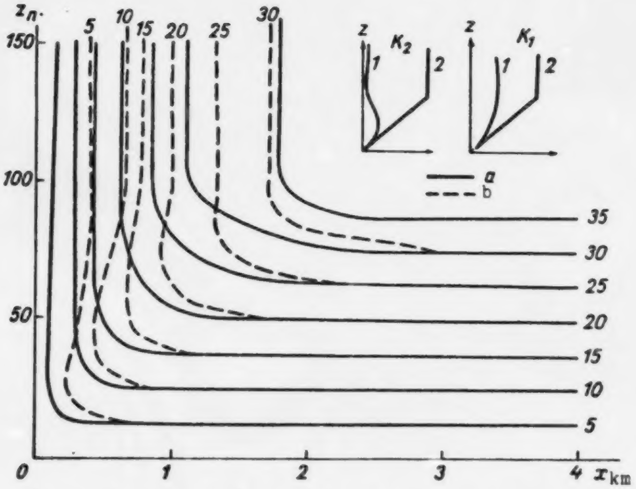

Fig. 2. Isolines $k_1$ (z, x) (a) and $k_2$ (z, x) (b) and typical profiles of $k_1$ and $k_2$ at distances of 0.2 km (1) and 4 km (2).

Considering the wind velocity profile in the surface layer to be logarithmic (indifferent stratification), one can calculate the dependence of $k_o$ and $\tau_L$ on height [8]. Figure 2 shows isolines of k for vertical diffusion, calculated for the atmospheric surface layer to a height of 100 m. Above that, the layer is considered homogeneous. Solid lines indicate $k_1$ (for a stationary plume), and dashed lines, $k_2$ - for an instantaneous puff. In the right corner are shown the profiles of $k_1$ and $k_2$ at distances of 0.2 km (1) and 4 km (2) from the source. At the 4 km distance, the usual profile of k (with a discontinuity) is observed, but at a close distance it differs markedly from the limiting one. Saturation takes place faster near the earth than in the upper layers, since $\tau$ increases with height.

The magnitude of $x_L$ in the layer above 100 m in indifferent stratification amounts to 500-1000 m for vertical and 2000-5000 m for transverse diffusion. That is why the change of the vertical diffusion coefficient with distance is usually neglected, something that cannot be done with the horizontal diffusion coefficient.

A similar method of calculating the dispersion of particles by turbulent fluctuations [method of Khey (Hay) and Pasquill (14, 17)] is widely employed in American and British studies. They use the spectral approach, which is based on some assumptions concerning the relationships between the Eulerian and Lagrangian spectra of wind velocity fluctuations. Although these assumptions are not rigorous, they yield satisfactory results in practical calculations. The key quantity in this approach is the ratio of the Lagrangian to the Eulerian time scale

$$\beta = \tau_L / \tau_E = \frac{\tau_L U}{r_E}, \tag{17}$$

which depends on the character of turbulence, i.e., on stratification and other conditions, and requires further experimental studies.

Let us now consider certain special problems that are solved by applying the above method. Let us note at once that these solutions are approximate mainly because of an inadequate knowledge of the properties of the velocity correlation functions. In this paper, we present solutions that were obtained on the basis of reduced expressions for these functions, and therefore good quantitative agreement between the theoretical calculations and the experimental data cannot be expected in all cases. However, it will be possible to refine these solutions after more complete information is obtained on Lagrangian velocity correlation functions under conditions of real atmospheric turbulence, and such experimental studies are being extensively conducted at the present time.

## 2. Diffusion from a Point Source of Finite Time of Action

As our first problem we will consider the calculation of the dispersion of impurity particles from a source with a finite time of action, or, what amounts to the same thing, the dispersion of impurity particles from a stationary plume, but with a finite measurement interval. This problem is frequently of practical importance, since for a normal particle distribution in the plume, other things being equal, the axial, i.e., maximum possible concentrations are inversely proportional to the horizontal and vertical dimensions of the plume. Obviously, if the diffusion along the wind direction is neglected, the total dispersion of the "shortened" plume (i.e., formed during a finite time) is determined by the superposition of instantaneous plumes during this time interval regardless of whether this interval is the time of action of the source or the time of observation.

The scheme of the calculation*, based on the above considerations, is shown in Fig. 3. In the latter, y (t, τ) is the coordinate of a particle that has left the source at time t and wandered during a time τ. Having used the expression for the dispersion of a random quantity calculated from a statistical ensemble of shortened realizations of duration T, for a fixed τ, we obtain

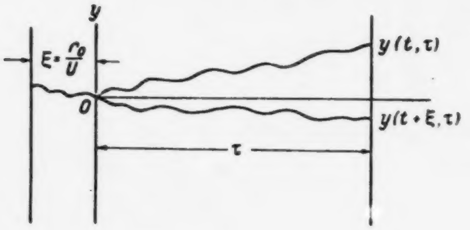

Fig. 3. Diagram for the calculation of the dispersion of particles from a source of finite time of action.

$$\sigma_T^2(\tau) = \frac{1}{T}\int_0^T [y(t,\tau) - \langle y_T(\tau)\rangle]^2\, dt =$$

$$= \sigma_1^2(\tau) - \frac{2}{T^2}\int_0^T (T-\xi) R_y(\xi,\tau)\, d\xi, \tag{18}$$

where $\sigma_1^2(\tau)$ is determined from (7) and (11),

$$\langle y_T(\tau)\rangle = \left\langle \frac{1}{T}\int_0^T y(t,\tau)\, dt \right\rangle,$$

$$R_y(\xi,\tau) = \langle y(t,\tau)\, y(t+\xi,\tau)\rangle. \tag{19}$$

The coordinate y (t,τ) may be obtained by integrating the particle velocity from the time of its escape from point ($x_0$, $y_0$) to time τ determining its distance to the source. Having denoted the velocity of such a particle by υ ($x_0$/t, s), where t signifies that at point $x_0$ the particle was located at time τ, we have

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* Coincides with the scheme used in [3]

$$y(t, \tau) = \int_0^t v(x_0/t, s)\,ds, \tag{20}$$

whence

$$R_y(\xi, \tau) = \int_0^\tau \int_0^\tau \langle v(x_0/t, s')\, v(x_0/t+\xi, s'') \rangle\, ds'\, ds''.$$

The function under the integral sign is the velocity correlation function of two particles, and at the instant the first of these passed through point $x_o$, the second was located at a distance $r_o$ from it; under the assumption of frozen turbulence, it may be considered that $r_0 = U\xi$. Having used expressions (12) and (13) to find it, and carried out the integration, we obtain

$$R_y(\xi, \tau) = \sigma_0^2(\tau)\left[1 - \frac{D(U\xi)}{2\langle v^2\rangle}\right], \tag{21}$$

where $\sigma_o^2(\tau)$ is determined from (15). Substituting (21) into (18), we have

$$\sigma_y^2(\xi) = \sigma_1^2(\xi) - \sigma_0^2(\xi)\,\varphi(\eta) = \sigma_2^2(\xi) + \sigma_0(\xi)\,[1 - \varphi(\eta)] \tag{22}$$

$\left(1 - \frac{D(r_0)}{2\langle v^2\rangle} = R(r_0)\right.$ being the normalized Eulerian spatial correlation function);

$$\varphi(\eta) = \frac{1}{\eta^2}\int_0^\eta (\eta - \xi)\, R(r_E; \xi)\, d\xi, \tag{23}$$

$r_E$ being the Eulerian spatial scale.

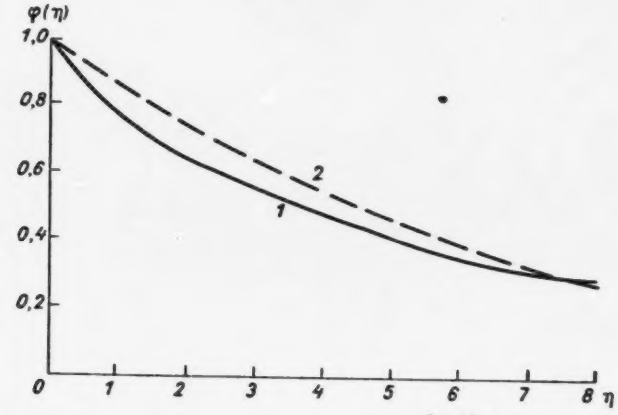

Fig. 4. The function $\phi(\eta)$ for $R = e^{-\left(\frac{r}{r_E}\right)^{2/3}}$ 1) and $R = e^{-r/r_E}$ 2).

Thus, according to (22), the shortened dispersion is equal to the difference between the dispersion of the stationary plume and the dispersion of the centers of gravity, multiplied by a correction factor dependent on T. By giving a different form to the function D $(r_o)$, or, what amounts to the same thing, R $(r_o)$, one can obtain the concrete form of this factor. In particular, for $D(r)=C(\varepsilon r_0)^{2/3}$ (inertial interval), $R(r)=e^{-r/r_E}$ and

$R(r)=\exp(-r/r_E)^{2/3}$ we obtain

$$\varphi(\eta)=C\frac{(\varepsilon UT)^{2/3}}{\langle v^2\rangle}, \tag{24}$$

$$\varphi(\eta)=\frac{2}{\eta^2}(\eta+e^{-\eta}-1),$$

$$\varphi(\eta)=\frac{6}{\eta^2}\left[(1+\eta^{2/3})e^{-\eta^{2/3}}+\frac{\sqrt{\pi}}{4}\Phi(\eta^{1/3})-1\right],$$

where

$$\Phi(z)=\frac{2}{\pi}\int_0^z e^{-z^2}dz.$$

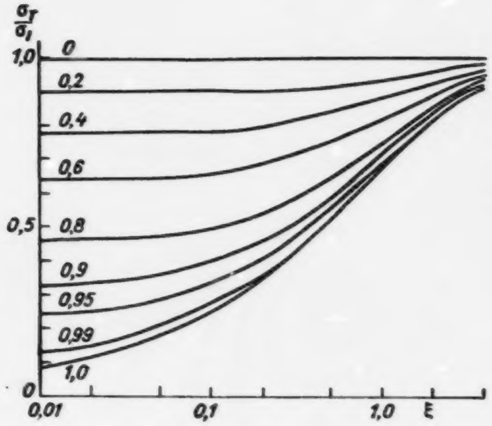

Fig. 5. $\sigma_T/\sigma_1$ versus $\xi$ for different values of $\phi(\eta)$.

The functions $\phi(\eta)$ are shown in Fig. 4. Since for short averaging times $\phi(\eta) \to 1$, and long ones $\phi(\eta) \to 0$, we have

$$\sigma_T^2(\tau)\to\sigma_1^2(\tau) \quad \text{при} \quad T\to\infty,$$
$$\sigma_T^2(\tau)\to\sigma_2^2(\tau) \quad \text{при} \quad T\to 0.$$

Let us note that when $\xi \ll 1$ (i.e., for short diffusion times near the source), expression (22) takes the simple form

$$\sigma_T^2(\tau) = \langle v_T^2 \rangle \tau^2, \qquad (25)$$

where

$$\langle v_T^2 \rangle = \langle v^2 \rangle - \frac{2}{T^2} \int_0^T (T - \xi) R(\xi) \, d\xi$$

is the dispersion of the velocity fluctuations, calculated from the shortened Eulerian realization of length T.

When $\xi \ll 1$ and $\eta \ll 1$, i.e., for small T and $\tau$, we have

$$\sigma_T^2(\xi) = \frac{2 \langle v^2 \rangle \tau^3}{3 \tau_L} + 0{,}45 \left( \frac{T}{\tau_E} \right)^{2/3} \langle v^2 \rangle \tau^2. \qquad (26)$$

If the second term in expression (26) predominates, the source may be considered quasi-permanent; in the opposite case, when $0{,}675 \left( \frac{T}{\tau_E} \right)^{2/3} \ll \frac{\tau}{\tau_L} \ll 1$ it is quasi-instantaneous. Figure 5 gives the dependence of $\sigma_T/\sigma_1$ on $\xi$ for different values of $\phi(\eta)$.

Results of experiments conducted at the Institute of Experimental Meteorology for different times of action of the source [11] show a fairly good qualitative agreement with the results of calculations, but no quantitative agreement was obtained. This appears to be due to the influence of large-scale eddies of quasi-periodic structure which, according to several studies [9], are observed in the atmosphere mainly with an unstable stratification. The correlation functions used in the calculation do not take this into account.

## 3. Dispersion of Heavy Particles in a Turbulent Atmosphere

In his study [16], M. I. Yudin formulated three mechanisms of the influence of gravity settling of particles on diffusion in a turbulent medium. The first mechanism - displacement of the center of gravity of the particle cloud - is considered by a suitable term in the semiempirical equation of turbulent diffusion. The second mechanism involves the fact that because of their size and inertia, the particles do not fully acquire the high frequency fluctuations of the medium (this mechanism was examined in several studies [17, 12]; even in the diffusion of fairly heavy, but fine particles in a turbulent atmosphere, the effect of this mechanism may be neglected. The third mechamism is associated with the fact that during its fall, a heavy particle intersects the trajectories of the surrounding air particles, falling successively into the range of influence of different eddies. A calculation of the influence of this effect was made for a continually acting source by Yudin [16] and for a cloud of individual particles by Smith [13, 17]. The present study gives a certain generalization of the results of [16].

In conformity with Yudin's ideas, the calculation will be made by using expression (7), where the velocity correlation function

$$R_L(\tau) = \langle v(x_0,\ t)\, v(x_0,\ t+\tau)\rangle \tag{27}$$

should be taken along the mean trajectory of the motion of the scattering particles. (Here $v(x_0,\ t)$ is the fluctuation velocity of the particle at time t, particle that at $t = 0$ was located at a point with coordinate $x_0$).

Let us consider two limiting cases. If the gravity settling rate w of the particles is small compared with the fluctuation velocity in the direction of diffusion v, so that during the correlation time the particle is unable to excape to any appreciable extent from the effective range of these eddies (which were acting on it at the instant of escape from the origin of coordinates), the particle may be considered practically weightless, and the Lagrangian time correlation function $R_L(\tau)$ may be used in expression (27).

In the other limiting case, when $w \gg v$, the particles escape along the direction of action of the gravity force so rapidly that the loss of the Lagrangian correlation will not be able to manifest itself. The reason for loss of the correlation in this case will be the particle displacement in space, and in expression (27) it is necessary to take the Eulerian space correlation function

$$R_E(r) = \langle u(x_0,\ z,\ t)\, u(x_0,\ z+r,\ t)\rangle, \tag{28}$$

where u (x, z, t) is the Eulerian particle velocity.

In the intermediate case, the velocity correlation function must be taken with a certain approximation along the mean path of the incident particles:

$$R_w(r,\ \tau) = \langle v(x_0,\ z,\ t)\, v(x_0,\ z+r,\ t+\tau)\rangle, \tag{29}$$

where $r = wt$. Expression (29) constitutes a mixed space-time velocity correlation function of a fluid particle. Its dependence on the time and coordinates is known only in the inertial range along the coordinate axes:

$$R_w(r,\ 0) = R_E(r) = \langle u^2\rangle\left[1 - \left(\frac{r}{r_E}\right)^{2/3}\right], \tag{30}$$

$$R_w(0,\ \tau) = R_L(\tau) = \langle v^2\rangle\left[1 - \frac{\tau}{\tau_L}\right], \tag{31}$$

where $r_E$ and $\tau_L$ are the spatial Eulerian and temporal Lagrangian turbulence scales. It is assumed that $\langle u^2\rangle = \langle v^2\rangle$.

Taking $R_w(r, 0) = 0$ for $r > r_E$ and $R_w(0, \tau) = 0$ for $\tau > \tau_L$, Yudin constructed the majorant and minorant of the function $R_w(r, \tau)$, which made it possible to calculate the dependence of $k_w = \frac{1}{2} \frac{d\sigma^2}{dt}\Big|_{t\to\infty}$ from w in two variants, with the true values of $k_w$ located between these variants. The relatively inconvenient form of correlation functions (30) and (31) made it impossible to obtain this dependence in the analytical form for any w; in the limit, $k_w \to A \frac{v}{w}$ for $w \to \infty$ (A is some constant determinable from the relationship of the Eulerian and Lagrangian turbulence scales).

In order to obtain more obvious results, it is expedient to set approximately

$$R_L(\tau) = \langle v^2 \rangle e^{-\tau/\tau_L}, \tag{32}$$

$$R_E(r) = \langle v^2 \rangle e^{-r/r_E^*}. \tag{33}$$

Expression (33) is obviously a poor approximation of the "two-thirds law" for small r's, but in view of the fact that it enters into the final result under the integral sign, it is not very important. (To preserve the scale relationship, it is necessary to set $r_E^* = 1{,}25 r_E$.)

It may be approximately assumed that

$$R_w(r, \tau) = \langle v^2 \rangle \exp\left[-\sqrt{\left(\frac{\tau}{\tau_L}\right)^2 + \left(\frac{r}{r_E^*}\right)^2}\right]. \tag{34}$$

As can be readily ascertained, the expression

$$R_w(r, \tau) = \langle v^2 \rangle e^{-\frac{\tau}{\tau_L} - \frac{r}{r_E^*}}. \tag{35}$$

corresponds to the interpolation over the minorant used in [16].

Setting r = wt and integrating expression (7) with $R_w$ values from (34) or (35), we obtain

$$\sigma_w^2 = \frac{2\langle v^2 \rangle \tau_L^2}{\varphi^2(s\nu)} \left[\frac{\tau}{\tau_L^w} - 1 + e^{-\tau/\tau_L^w}\right], \tag{36}$$

where

$$\tau_L^w = \tau_L/\varphi(s\nu); \quad \nu = \frac{w}{\sqrt{\langle v^2 \rangle}}; \quad s = \frac{\tau_L \sqrt{\langle v^2 \rangle}}{r_E^*}.$$

For variant (34), $\varphi(s\nu)=\sqrt{1+s^2\nu^2}$.

For variant (35), $\varphi(s\nu)=1+s\nu$.

Comparing (36) with (11), we see that the expression for $\sigma_w^2$ differs from the analogous expression in the case of w = 0 only in the fact that the scale $\tau_L$ is replaced by $\tau_L^w$.

For the turbulent diffusion coefficient of heavy particles $k_w$, we have in this case for $v \to \infty$:

$$\frac{k_w}{k_0}=\frac{1}{\varphi(s\nu)}\to\frac{1}{s\nu}=\frac{r_E^*}{w\tau_L}, \qquad (37)$$

which agrees with the limiting dependence, in conformity with (16) and (13).

Assuming, according to the frozenness hypothesis, that $r_E=U\tau_E$, where U is the mean wind velocity, we have

$$s\nu=\frac{\tau_L}{\tau_E}\,\frac{w}{1{,}25U}.$$

Figure 6 gives the dependence of $k_w/k_o$ on the parameter $v$. At the same time, it gives the scale $v = \frac{\omega}{\nu}$ with the provision that the value of s is determined only by the inertial interval (in this case $s \approx 1.8$). The figure also gives the curves taken from [16], obtained from the majorant and minorant; the latter dependence nearly coincides with the dependence (37), with condition (35). Figure 6 shows that the influence of $\omega$ on K begins to be manifested in the range of 10% for $sv$ = 0.3, and above 50% for $v$ = 2.

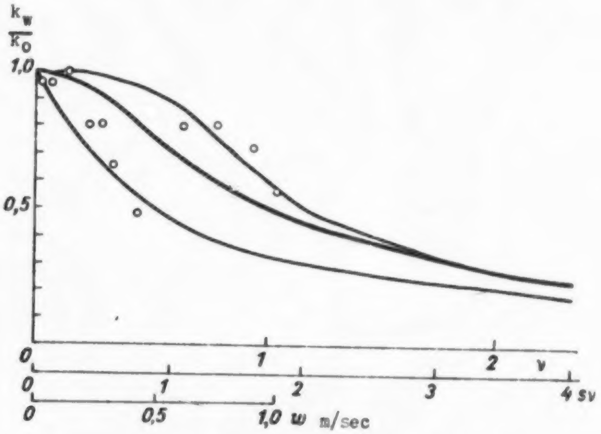

Fig. 6. Dependence of $\frac{k_w}{k_o}$ on $v$ and $sv$.

To check the relations obtained, it is necessary to carry out experiments on the spreading of particles at different gravity settling rates from a point source under the same meteorological conditions. In order to detect the effect described, the precision of the experimental set-up should be sufficiently high. There are almost no experimental results available that satisfy these conditions and that could be compared with calculated data, so that at the present time the comparison can only be qualitative. Figure 6 also shows results of calculations of the vertical turbulent diffusion coefficient as a function of w, obtained in [6] on the basis of experiments described in [5]. The scale of w was chosen so that the experimental points fell as nearly as possible on the calculated curve. Knowing the mean wind velocity, one can determine from the scale relationship the approximate value of $\beta = \frac{\tau_L}{\tau_E}$, which in this case is found to be approximately equal to 10.

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## THE METHOD OF ATMOSPHERIC DIFFUSION EVALUATION ON TURBULENT CHARACTERISTICS *

The pollutant distribution in turbulent atmosphere is discussed with the help of Lagrangian method. Approximate connection between Lagrangian and Eulerian turbulent characteristics is used for evaluation of turbulent diffusion parameters. The diffusion parameter estimations for boundary air layer are given. The comparison with semi-empirical methods of pollutant distribution calculation is done. This method allows to consider some specific problems, in particular, to evaluate the influence of gravitational sedimentation on diffusion parameters taking into account correlation loss because of particle displacement in the process of vertical motion, to obtain formulas for dispersion calculation of diffusible pollutant from a point source of finite operation time (this problem is equivalent to the problem of finite time of diffusion measurement from the source of infinite operation time).

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* Editor's note: The abstract is presented as given in English with the original Russian article.

# SCATTERING OF SMOKE FROM A HIGH-LEVEL POINT SOURCE

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In calculations of the scattering of an impurity from a point source, the greatest difficulty lies in calculating the scattering in the cross-wind direction. In this connection, both theoretical and experimental studies of this phenomenon are being conducted at the Institute of Experimental Meteorology. Ivanov [5] and Byzova [2] have presented an outline of results of theoretical studies which made it possible to develop a procedure for calculating the scattering. In the present report, an evaluation of the procedure and its scope of applicability is made on the basis of experimental data. The concepts and arbitrary notation fully correspond to the studies [5, 2].

## Experimental Procedure

In the present study, the investigation of the scattering of a light impurity in the horizontal plane from a high-level point source involved the use of oblique photography of smoke plumes, made from a 300-meter meteorological mast.

To obtain the scattering parameters, it is necessary to use some model of a smoke plume. We used as the basis Gifford's statistical model [4], which corresponds most closely to actual plumes. The statistical model consists of a set of discs with a Gaussian distribution of matter; the centers of gravity of the discs are subjected to random oscillations relative to the wind direction. Scattering along the x axis is neglected. It follows from this model that the dispersion of the impurity distribution for an averaged plume is equal to the sum of the dispersion of the impurity distribution relative to the instantaneous plume axis and dispersion of the coordinates of the instantaneous axis relative to the averaged plume axis. The x axis coincides with the average wind direction, the y axis is perpendicular to it, and the z axis is directed vertically upward.

For dispersion along the y axis, we have

$$\sigma_1^2 = \sigma_2^2 + \sigma_0^2. \tag{1}$$

Photography of the smoke plumes gives direct information on the geometric shape of the plume, which can be converted to dispersion values. Thus, using the expression for the instantaneous distribution of the smoke concentration

$$q = Q\left[2\pi\bar{u}\left(\sigma_{2y}^2\,\sigma_{2z}^2\right)^{\frac{1}{2}}\right]^{-1} e^{-\frac{(y-D_y)^2}{2\sigma_{2y}^2}-\frac{(z-D_z)^2}{2\sigma_{2z}^2}}, \qquad (2)$$

where Q is the output of the source, $\bar{u}$ is the average wind velocity at the source level, and $D_y$ and $D_z$ are the coordinates of the axis of the instantaneous plume; one can obtain $\sigma_{2y}^2$ by integrating with respect to z and assuming that the concentration is constant everywhere over the contour of the plume, in accordance with Robert's "transparancy theory" [12]. In this case, we obtain

$$q_0 = Q\left[2\pi\sigma_2^2\right]^{-\frac{1}{2}}\bar{u}^{-1} e^{-\frac{y-D_y}{2\sigma_{2y}^2}} = \text{const.} \qquad (3)$$

Taking logs of (3) and differentiating, we get the expression

$$\frac{1}{\sigma_2^2}\frac{d\sigma_2^2}{dt} = \frac{(y-D_y)^2}{\sigma_2^2}\frac{d\sigma_2^2}{dt} - \frac{2(y-D_y)}{\sigma_2^2}\frac{d}{dt}(y-D_y). \qquad (4)$$

from which it follows that at time t, when y - $D_y$ is maximum,

$$(y-D_y)^2_{\max} = \sigma_2^2. \qquad (5)$$

Using the values of $q_o$ at the end of the plume, and also relations (3) and (5), we finally obtain

$$\sigma_2^2\left(\frac{x}{\bar{u}}\right) = \frac{(y-D_y)^2}{\ln e(y-D_y)^2_{\max} - \ln\sigma_2^2\left(\frac{x}{\bar{u}}\right)}. \qquad (6)$$

Hence, one can study $\sigma_2^2$ as a function of t without specifying the form of the function $\sigma_2^2$, and use $\sigma_2^2$ in calculations with formula (1). The magnitude of $\sigma_0^2$ is determined directly from photographic data.

To obtain the geometric characteristics of the smoke plume, we used oblique photography by means of an aerial camera. A picture obtained by this method constitutes the central projection of the smoke plume and background of the terrain over which it extends [1]. Fig. 1 shows how the perspective representation of a smoke plume is made, and also the basic elements of the central projection, where P is the object plane, or plane of propagation of the smoke plume; K is the plane of the photograph; S is the projection center; O is the principal point of the picture; SO is a perpendicular to the plane of the picture, equal to the focal distance of the camera; SN is the distance from the projection center to the object plane, called the terrain clearance and equal to the height of the camera above the smoke source (SN = H); n is the nadir point, i. e., the trace of the ray SN on the plane of the picture; $\alpha$ is the angle formed by the principal direction SO with the plumb line and equal to the angle between the picture plane and the object plane.

By passing the vertical plane through rays SO and SN at right angles to planes K and P, its intersection with the picture plane gives the prime vertical, and the intersection with the object plane gives the photographic line of direction NO. In Fig. 1, the x axis of the picture coincides with the direction of the prime vertical, the y axis is parallel to the line of visible horizon hh, and the X axis coincides with the photographic line of direction. When the origin of coordinates of the picture is chosen at the nadir point, the coordinates of the points of the smoke plume are related to the points corresponding to them on the picture by the following simple formulas (4):

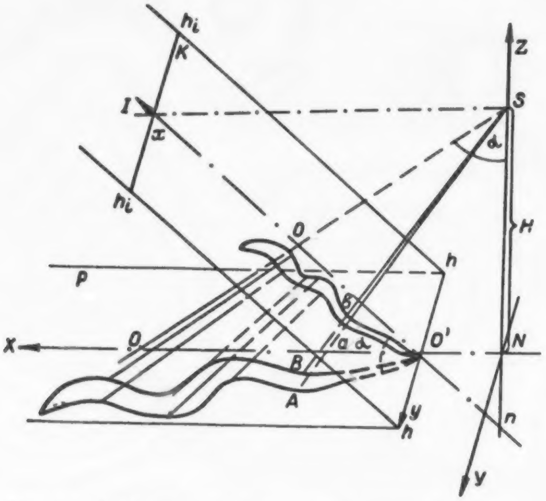

Fig. 1. Oblique representation of smoke plume

$$X = \frac{H}{f} x \frac{\cos^2 \alpha}{1 - \frac{\cos \alpha \sin \alpha}{f}};$$

$$Y = \frac{H}{f} y \frac{\cos \alpha}{1 - \frac{\cos \alpha \sin \alpha}{f}}, \qquad (7)$$

which describe the variation of the image scale with the angle of inclination of the camera.

To estimate the relative values of X and Y after taking logs and differentiating, we have

$$\frac{dX}{X} = \frac{dH}{H} + 2\tan\alpha\, d\alpha + \frac{dx}{x} + \frac{d\,(x\sin\alpha\cos\alpha)}{f - x\sin\alpha\cos\alpha};$$
$$\frac{dY}{Y} = \frac{dH}{H} + \tan\alpha\, d\alpha + \frac{dy}{y} + \frac{d\,(x\sin\alpha\cos\alpha)}{f - x\sin\alpha\cos\alpha}. \qquad (8)$$

It follows from (8) that the errors in the difference of height H and in the value of $(f-x\sin\alpha\cos\alpha)$ cause a regular distortion of coordinates X and Y; errors in the measurement of x and y cause proportional errors in the measurement of X and Y; the error due to the angle of inclination is proportional not only to the precision of measurement of the angle, but also to the tangent of the angle of inclination, which increases rapidly with increasing $\alpha$. The most convenient angle of inclination of the camera at H = 200-300 m turns out to be 45°, since in this case the field of the picture is used to a maximum extent, and the line of the visible horizon is recorded; this line makes it possible to refine the angle of inclination of the camera to one minute, based on the magnitude of segment OI in Fig. 1, with the aid of the formula

$$OI = f/\tan\alpha,$$

the error due to $\alpha$ being determined only by the magnitude of $d\alpha$.

Formulas (8) do not consider all the errors inherent in the method. For example, errors in the determination of X and Y may be due to an inadequate flattening of the aerial film and deformation after the developing and fixing; in particular, there may be errors in the determination of the plume edge, owing to a lack of sharp image contrast. Substantial errors in the determination of the plume width and axis coordinates are introduced by oscillations of the plume in the vertical plane (Fig. 2).

The relationship between the height of the plume above the horizontal plane h, which we took as the object plane, and the displacement of the image $\delta_{rh}$ on the picture is given by the formula

$$\delta_{rh} = \frac{rh}{H}\left(1 - \frac{r}{2f}\cos\varphi\sin 2\alpha\right). \qquad (9)$$

where r is the radius vector drawn from the nadir point; $\phi$ is the angle made by the radius vector with prime vertical.

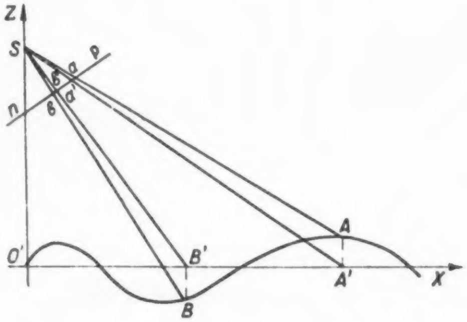

Fig. 2. Displacement of plume image due to oscillation in vertical plane.

In processing the pictures, one takes the cross sections of the smoke plumes along the y axis at predetermined distances x on the picture calculated from the first of formulas (7) and corresponding to fixed X values. Hence, vertical oscillation of the plume introduces errors only into the widths of the plume and into the axis coordinates; as the plume rises above the horizontal plane, the image of the plume (Fig. 2) moves away from the nadir point, and closer as the plume descends. In a stable atmospheric stratification, this error will be minimal; thus, for $h \leqslant 10$ m, $\alpha = 45°$, $H = 200$ m, $f = 70$ mm, and for maximum values $\phi = 20°$, $r = 130$ mm, $\delta_{rh}$ is equal to about 0.27 mm, or approximately 1%.

The relative error in the determination of the smoke plume edge reaches its largest value at the end of the plume, where the latter has least contrast and where for this reason a contour is outlined which introduces a certain arbitrariness and smoothing of the plume edge. In some cases, the error caused in this manner may reach 8-10%. The total maximum relative error in the determination of the plume width and ordinates of the axis depends on the portion of the plume and ranges from 3.5 to 11.5%. In an unstable atmospheric stratification, when the plume oscillations in the vertical plane are large, the accuracy of the method decreases considerably, and it is preferable to use stereophotogrammetry, which gives all three coordinates of the object studied, but is more complex and time-consuming.

The random error in the determination of $\sigma_2$ and $\sigma_0$, in contrast to the systematic error, whose sources and evaluation are indicated above, is much larger and also increases with the distance from the impurity source because the number of recorded plumes of the same length decreases in the course of the survey. The figures shown in this study give the total mean square errors of the measurements.

The experiments involved the use of an AFA-37 topographic aerial camera with $f = 70$ mm, a diagonal angular field of 122 , and a frame size of 18 by 18 cm. The AFA-37 takes pictures automatically at predetermined time intervals of 2 to 90 sec, and is equipped with a set of color and neutral filters and a vacuum pump to flatten the aerial film when the photographs are taken. To enable it to rotate around the vertical and horizontal axes, the camera is attached to a special tripod mounted at the 300-meter level of a high-level mast. The source of smoke (smoke charges) was placed at one of the levels (75, 100, 125 m) and was set out on a mast ledge perpendicular to the flow.

## Experimental Results

Table 1 lists data on the conditions of diffusion of the experiments, all of which were carried out in the evening or morning hours during a stable stratification of the atmosphere and at weak or moderate wind speeds in an $h_s$ layer of about 2.0 m. The magnitudes of the Monin-Obukhov scale L indicate that in all the experiments at source height $h_s$, the flow may be considered quasi-uniform. The initial size of the plume $y_0$ was equal to an average of 0.4 m.

Table 1

| Experiment number | Date | Time<br>Hr min | T, min. | $\Delta t$, sec. | Height, $h_{act}$, m | $\bar{u}_{2,0}$ m/sec | $\bar{u}_h$ m/sec | L, m | B |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 20/VII 1967 | 18 30 | 16,5 | 30 | 121,6 | 0,8 | 3,0 | 2,3 | 0,0382 |
| 2 | 14/IX | 18 00 | 15,0 | 30 | 75,0 | 0,0 | 1,7 | 0,28 | 0,6440 |
| 3 | 26/III | 11 00 | 7,0 | 15 | 97,0 | 2,7 | 4,6 | 7,5 | 0,1134 |
| 4 | 18/IV 1968 | 19 00 | 9,0 | 15 | 97,0 | 1,4 | 4,0 | 40 | 0,0065 |
| 5 | 5/V | 19 21 | 16,0 | 15 | 97,0 | 1,0 | 2,6 | 7,1 | 0,0378 |
| 6 | 6/V | 05 13 | 11,25 | 15 | 97,0 | 1,4 | 7,0 | 20 | 0,0133 |

An important parameter characterizing the relative scattering of particles in the plume is the relative dispersion of the impurity distribution, which we determine directly from experimental data by using formula (6). Expressions for the relative dispersion $\sigma_2^2$ are known in partial cases of short and long time of particle diffusion $(t - t_0)$. Reynold's number Re is large, and the investigated scale of the phenomenon satisfies the conditions $l_0 \ll \lambda \ll L$, where $l_0 \approx \nu^{-3/4}\varepsilon^{-1/4}$ is the internal scale of turbulence ($\nu$ is the viscosity of air and $\varepsilon$ the dissipation of energy), and L is the external scale. The latter regime corresponds to the inertial range of the turbulence spectrum and in this case, on the basis of similarity theory, Batchelor [10] found that $\sigma_2^2$ is determined by the rate of dissipation of turbulent energy $\varepsilon$, by the time t, and by the initial plume size $y_0$. If the initial plume size is small and the condition $\sigma^2 - y_0 \gg y_0$, is fulfilled, after a certain time interval the particles "forget" the initial distance, and $\sigma_2^2$ will then depend on $\varepsilon$ and t in such a way that

$$\sigma_2^2 = c\varepsilon t^3, \tag{10}$$

where c is a constant close to 0.4, in accordance with [3].

Experiments on relative diffusion carried out by different authors and compiled by Gifford [11] confirm the presence of this regime. The latter is also confirmed by our data, but, in contrast to the results of [11], they made it possible to follow the regime $\sigma_2^2 \sim t^3$ up to a period one order of magnitude greater, and to establish its limits. In Fig. 3, where the values of $\sigma_2^2$ and x are plotted on a log-log scale; the scale of this period for a stable stratification of the atmosphere at a height of about 100 m is 500-800 sec, and the distances are 2000 m. In some experiments, it was possible to follow the variation of $\sigma_2^2$ up to the limiting regime $\sigma_2^2 \sim t$, when the particles move independently, and

$$\sigma_2^2 \to \sigma_1^2,$$

where $\sigma_1^2$ is the structural function of a single particle.

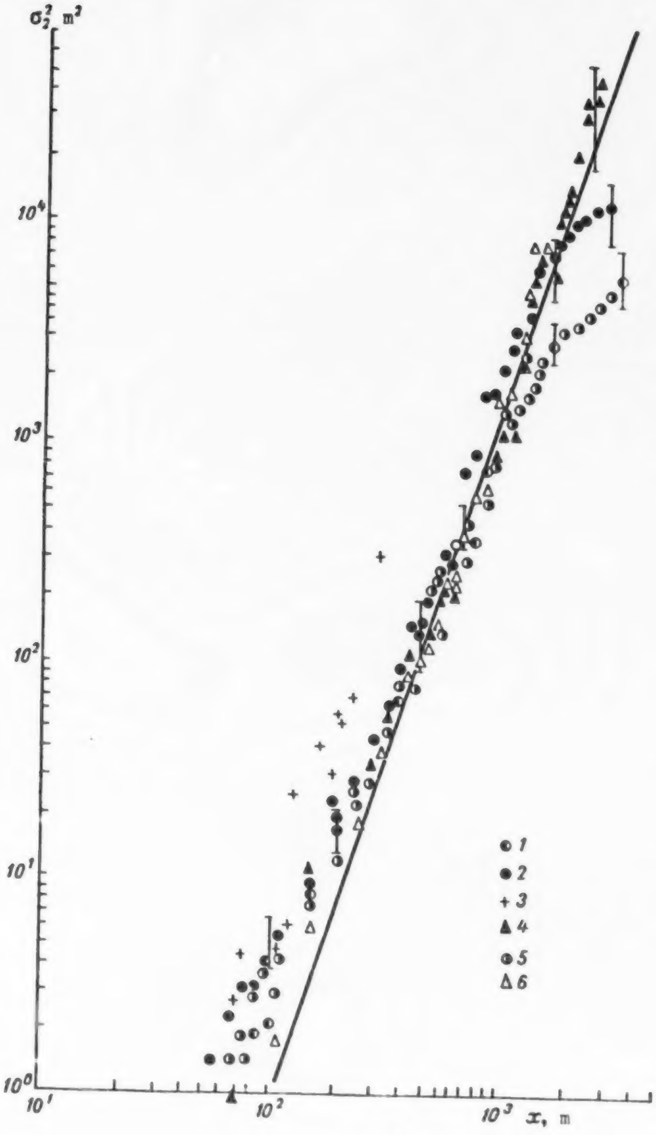

Fig. 3. $\sigma_2^2$ vs. $x$.
1-6 — numbers of experiments.

In [3], a type of correlation function of the distance between two "liquid particles" discussed in [9] was employed, and on the basis of similarity theory, an expression was obtained for the relative dispersion of the impurity distribution. This dispersion is determined by the two main parameters of turbulent flow, the turbulent energy $\overline{v^2}$ and its dissipation rate $\varepsilon$ :

$$\sigma_2^2 = 2\overline{v}^2\tau_L^2\left[t/\tau_L - \frac{3}{2} - \frac{1}{2}e^{-2t/\tau_L} + 2e^{-t/\tau_L}\right]. \qquad (11)$$

Here $\tau_L = \frac{\overline{v}^2}{c_1\varepsilon}$ is the Lagrangian time scale.

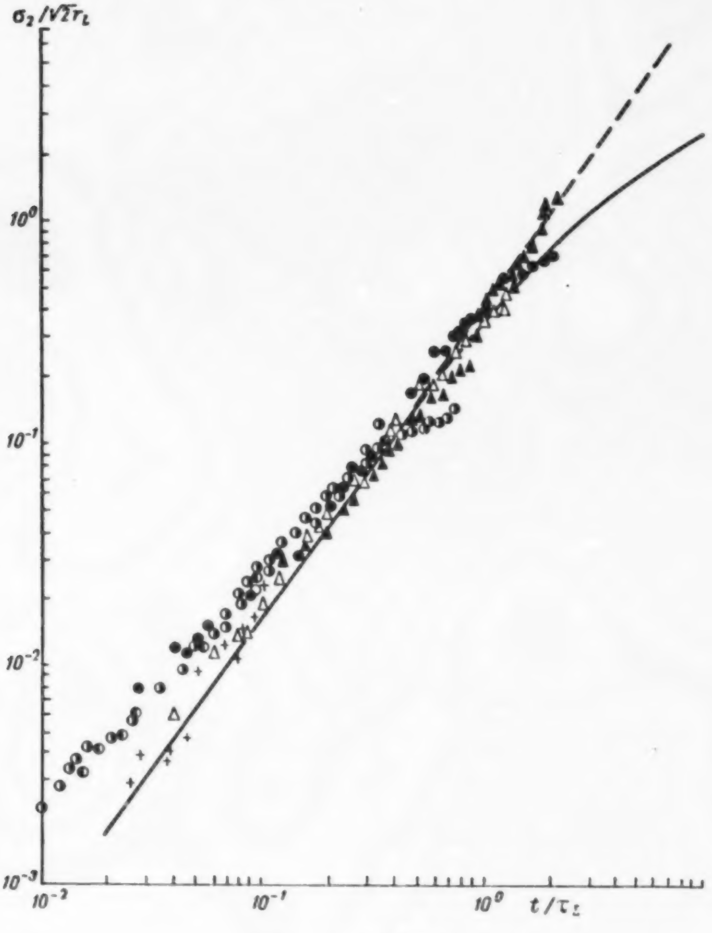

Fig. 4. $\sigma_2/\sqrt{2}\,r_L$ vs. $t/\tau_L$.

The quantity $\overline{v^2}$ was determined from measurements of $\sigma_1^2$ by using Taylor's limiting formula

$$\sigma_1^2 = \overline{v}^2 t^2$$

for small t, and $\varepsilon$ was determined by interpolating measurements of $\sigma_2^2$ with formula (10). In Fig. 4, the experimental data are plotted on a log-log scale. The solid line shows function (11), and the dashed line, the asymptote $\sigma_2 = (c\varepsilon t^3)^{1/2}$. The magnitude of the diffusion scale is equal to $\sqrt{\overline{v^2}}\tau_L$.

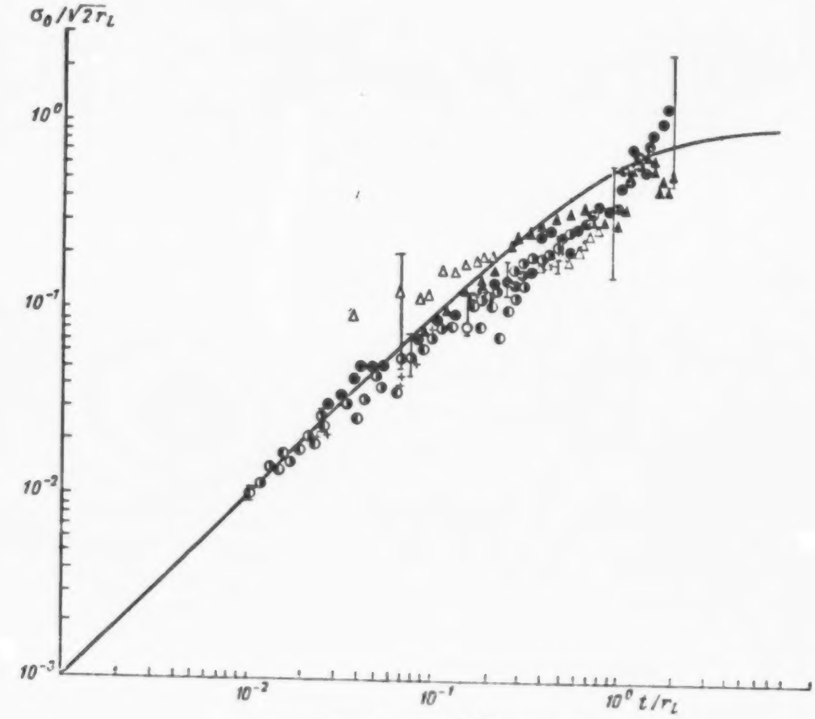

Fig. 5. $\sigma_0/\sqrt{2}\tau_L$ vs. $t/\tau_L$.

Comparison of the theoretical curves with the experiment shows their satisfactory agreement up to $t/\tau_L = 1.0$, with the exception of the fifth experiment, in which deviation from the asymptote 3/2 occurred sooner, when $t/\tau_L = 0.35$. A certain discrepancy at short diffusion times can be explained by the presence of a considerable transition period from the $\sigma_2^2 \sim t^2$ to the $\sigma_2^2 \sim t^3$ regime, recorded by measurements, and also explained by the influence of the aerodynamic shadow of the high-level mast.

In contrast to $\sigma_2$, the dispersion of the ordinates of the instantaneous axis $\sigma_0$ is measured directly from data of the photographs without any additional hypotheses. This is a distinct advantage of the proposed procedure and makes it possible to study the oscillations of the plume axis in pure form.

Whereas relative diffusion makes it possible to study the influence of small-scale eddies comparable to the plume width on impurity scattering, oscillations of the instantaneous plume axis make it possible to evaluate the influence of eddies of much larger size.

In [6], an expression was obtained for $\sigma_0^2$ based on the similarity theory for the inertial range, the extrapolation form of which is

$$\sigma_0^2 = 2\overline{v^2}\tau_L^2\left(\frac{1}{2} - e^{-t/\tau_L} + \frac{1}{2}e^{-2t/\tau_L}\right). \qquad (12)$$

From (12) it follows that at low t's, the growth of $\sigma_0^2$ is determined by $\overline{v^2}$, and afterward it slows down and tends to $r_L^2$ in the limit. This practically means that when $t \gg \tau_L$, the contribution of $\sigma_0^2$ is small, and the splitting of the scattering processes in two is no longer valid. This may serve as an independent estimate of $\tau_L$.

In Fig. 5, the experimental data are given on a log-log scale for relative coordinates, and the solid curve gives function (12). We should point out the good agreement between the calculated and experimental data for small values of $t/\tau_L$. For large $t/\tau_L$, despite a certain scatter, all the experimental points fall slightly below the calculated curve, which may be accounted for by an insufficiently long period of observation at the corresponding distances.

## Dispersion of the Impurity Distribution of an Averaged Smoke Plume

Using measured data on $\sigma_0^2$ and $\sigma_2^2$ and formula (1), one can obtain the quantity $\sigma_1^2$, which characterizes the scattering of an impurity in an averaged smoke plume. The following expression is derived in [3, 6, 7]:

$$\sigma_1^2 = 2\overline{v^2}\tau_L^2\left(t/\tau_L + e^{-t/\tau_L} - 1\right). \qquad (13)$$

Figure 6 represents plots of relative values of $\sigma_1$ obtained experimentally, and theoretical curves corresponding to $\sigma_1$ and $\sigma_2$.

From a comparison of the experimental and theoretical data it follows that the experimental points fall satisfactorily on the curve of $\sigma_1$ for small $t/\tau_L$, since the observation periods for these distances are sufficient to give reliable estimates of $\sigma_1$. At distance approaching $x/x_L = t/\tau_L$, the experimental data fall between the two limiting curves of $\sigma_1$ and $\sigma_2$ corresponding to dispersions from a continuous and an instantaneous source of impurity; this is due to the effect of the limited duration of observation periods of $\sigma_1$.

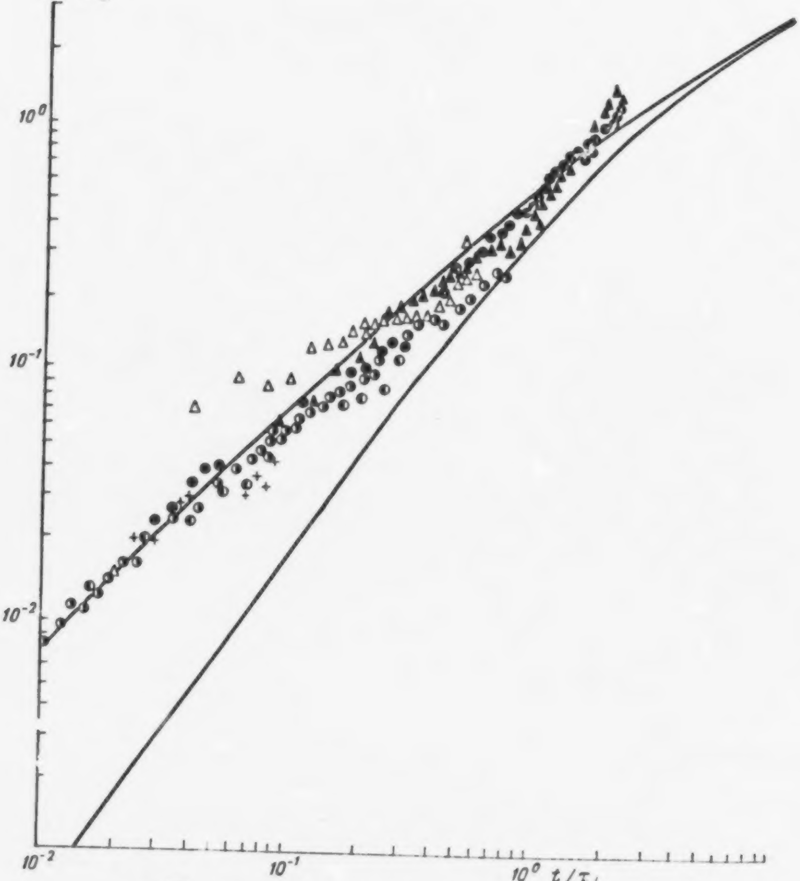

Fig. 6. $\sigma_1/\sqrt{2}\, r_L$ vs. $t/\tau_L$. Upper curve corresponds to expression (13), lower curve, to expression (11).

Table 2 shows values of $\varepsilon$ and $\sqrt{\overline{v'^2}}$ obtained from direct measurements of the longitudinal wind velocity component (a) from the high-level mast and from diffusion experiments (b). The anisotropy coefficient was taken as 0.75 [3]; the procedure for calculating $\varepsilon$ is described in [8]. We can point out the good agreement of $\sqrt{\overline{v^2}}$ values and a somewhat poorer agreement of values. The latter, obtained from diffusion data, are an average of 1.4 times smaller than ε values established from structural measurements on the mast. Table 2 also gives values of $\tau_L$, $x_L$ and $k_y$, which can be used to estimate these quantities in the boundary layer of the atmosphere for a stable stratification.

Table 2

| Experiment No. | $\varepsilon$, cm$^2$/sec |  | $\sqrt{\overline{v^2}}$ m/sec |  | $\tau_l$, sec |  | $x_l$, m |  | $k_y$, m$^2$/sec. |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  | a | b | a | b | a | b | a | b | a | b |
| 1 | 0,65 | 1,0 | 0,18 | 0,22 | 850 | 736 | 2490 | 2208 | 27,0 | 35,0 |
| 2 | 0,21 | — | 0,11 | — | 941 | — | 1600 | — | 11,0 | — |
| 3 | 13,0 | 20,0 | 0,66 | 0,64 | 568 | 348 | 2610 | 1600 | 250,0 | 140,0 |
| 4 | 2,2 | 4,0 | 0,24 | 0,26 | 436 | 288 | 1750 | 1110 | 25,0 | 20,0 |
| 5 | 0,4 | 0,5 | 0,23 | 0,25 | 2200 | 2080 | 5720 | 5420 | 120,0 | 130,0 |
| 6 | 4,8 | 5,8 | 0,36 | 0,31 | 450 | 370 | 3100 | 2600 | 58,0 | 35,0 |

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*E. K. GARGER*

# ON SMOKE DISPERSION FROM AN ELEVATED POINT SOURCE[*]

Measurements of smoke plume dispersion in horizontal plane were carried out from elevated point source situated at a height of 300m. Photogrammetric method of smoke plume fixing was used in this case.

The values of pollutant dispersion for instantaneous and averaged smoke plume and of dispersion of axis ordinates for instantaneous plumes were received. On the diffusive experimental data it was carried out an estimation of velocity of turbulent energy dissipation, Lagrangian time scale, and coefficients of turbulent mixing in cross-wind direction. The results were compared with analogous parameters received from structural measurements fulfilled at the same time with measurements of smoke plume dispersion.

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[*] Editor's note: The abstract is presented as given in English with the original Russian article.

# DIFFUSION FROM A POINT SOURCE OF FINITE TIME OF ACTION

Yu. S. Osipov (USSR)

From Glavnoe Upravlenie Gidrometeorologicheskoy Sluzhby Pri Sovete Ministrov SSSR. (Chief Administration of the Hydrometeorological Service Under the Council of Ministers of the USSR.) "Meteorologisheskie Aspekty Zagryazneniya Atmosfery". (Meteorological Aspects of Air Pollution.) Sbornik dokladov na mezhdunarodnom simpoziume v Leningrade - Iyul' 1968 g. (Reports delivered at the International Symposium in Leningrad - July 1968.) Pod redaktsiey d-ra fiz.-mat. nauk M. E. Berlyanda. (Edited by Prof. M. E. Berlyand.) Gidrometeorolgicheskoe izdatel'stvo, Leningrad, p. 207-214, (1971). (Hydrometeorological Publishing House, Leningrad, (1971).)

For a whole series of practical problems it is important to know the ways in which the average concentration of an impurity will vary with changing length of the observation interval. It is well known, for example, that even brief but substantial excess amounts over the maximum permissible concentration of an impurity in the atmosphere may cause enormous damage to human health and have a harmful effect on vegetation and crops. As was shown by experimental data, variations in impurity concentration with time are fairly substantial, and at certain moderate distances from the source, the maximum concentration may surpass the average value calculated from a 20-minute observation interval by one order of magnitude or more.

As an example, Fig. 1 shows the variation with time of the density of a deposit of aerosol particles 45-65 μm in size on the earth's surface at a distance of 300 m from a point source 75 m high. Sharp increases in density of the deposit with time are due to the movement of the impurity plume axis across the observation point. At the same time, one can see how much the 20-minute average, drawn on the graph as a dashed line, may be below the maximum values.

Within the framework of the statistical theory of atmospheric diffusion, the concentrations of a diffusing substance are determined via the dispersions of its distribution. To find the relationships between the maximum and average concentrations from a continuously acting source for different time intervals, it is necessary to know the regularities of the variation of this distribution as a function of the length of the observation interval.

This problem was discussed theoretically by I. Ogura [10, 11], E. K. Byutner [6], and N. L. Byzova [3], but the relationships they found are applicable only to rough estimates. For this reason, it is of interest to study the empirical characteristics of the dispersion of particles emitted by a point source of finite time of action. Such characteristics were found to be obtainable from the results of model experiments with fluorescent small particles 45-100 μm in size, conducted in 1966-67 from the 300-meter meteorological mast of the Institute of Experimental Meteorology. The procedure of such experiments has been described in detail in [1, 2].

A distinctive characteristic of the experiments of these two series was the fact that at the same level of the mast, two sources of an aerosol of different colors began to operate simultaneously, spraying the same amount of impurity over markedly different time intervals. The samples were collected on sticky boards previously emplaced in the zone of the presumed deposit. The dispersion $\sigma_b^2$ and $\sigma_1^2$ and the axial densities of the deposit $P_b$ and $P_1$ (subscripts b and 1 refer to the brief and lasting sources) were determined from the density of the impurity deposited on the boards, with the assumption that a normal distribution of its concentration takes place in the direction across the mean wind.

If the diffusion in the direction of the mean wind is neglected, and the adhesion of the impurity to the earth's surface is assumed to be complete, then in the board method of sampling, the time of action of the source may be considered equal to the time of deposition of the particles on the board, this being analogous to the time of averaging of the sample during its collection. Indeed, the time when we observe any particle at a certain distance from the source differs from the time of its escape from the source by the flight time t, and therefore the time interval during which we observe the particle from the first to the last at this distance is equal to the time interval during which the particles leave the source, with a shift by an amount t. This makes it possible to treat the time of action of the source as an analog of the time of observation of diffusion from a continuously acting source.

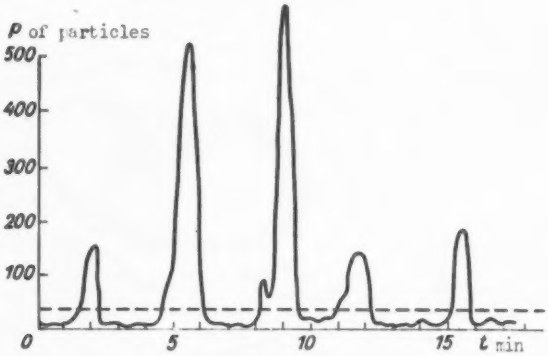

Fig. 1. Variation with time in density of deposit of impurity aerosol particles on the earth's surface at a distance of 300 m from a point source 73 m high.

The experimental results showed that as the duration of action of the source increases, so does the width of the pollution zone, and the axial densities of the deposit decrease, which is natural, since the total amount of impurity was the same in the brief and long emissions.

If the reduction in the axial density of the deposit were completely determined by the increase in transverse scattering of the impurity, we would have [5]

$$\frac{P_{\text{л}}}{P_{\text{к}}} = \frac{\sigma_{\text{к}}}{\sigma_{\text{л}}}. \tag{1}$$

However, as the duration of action of the source increases, the vertical scattering of the impurity also increases. For the isotropic case,

$$\frac{P_{\text{л}}}{P_{\text{к}}} = \frac{\sigma_{\text{к}}^2}{\sigma_{\text{л}}^2}. \tag{2}$$

If we consider that the contribution of vertical diffusion to the reduction of the axial density of the deposit is less than the contribution made by the increase of scattering in the cross-wind direction, since for the atmospheric boundary layer the size of turbulent eddies in the vertical direction is restricted by the earth's surface, then

$$\frac{\sigma_{\text{к}}^2}{\sigma_{\text{л}}^2} < \frac{P_{\text{л}}}{P_{\text{к}}} < \frac{\sigma_{\text{к}}}{\sigma_{\text{л}}}. \tag{3}$$

Table 1 gives average values of the ratios entering into (3), obtained from our experimental data. It is evident from the table that (3) is adequately confirmed.

Table 1

| Series | Period of Experiment | Number of Paired Experiments | $\frac{\sigma_b^2}{\sigma_1^2}$ | $\frac{P_1}{P_b}$ | $\frac{\sigma_b}{\sigma_1}$ |
|---|---|---|---|---|---|
| 1 | VIII—X 1963 r. | 2 | 0,42 | 0,56 | 0,64 |
| 2 | VI—VIII 1966 r. | 10 | 0,32 | 0,54 | 0,57 |
| 3 | II—III 1967 r. | 6 | 0,50 | 0,58 | 0,71 |
| 4 | VI—VII | 4 | 0,70 | 0,64 | 0,84 |
|  | Average total |  | 0,48 | 0,58 | 0,69 |

Simultaneously with the model experiment, measurements of the meteorological characteristics were made on the high-level meteorological mast. In addition to the mean velocity profiles (averaged over 10-minute observation intervals), wind direction, and temperature, measurements were also made on the kinetic energy of the longitudinal component $\overline{u^2}$ of the wind velocity fluctuations and on the rate of its dissipation $\varepsilon$. The procedure and apparatus for measuring the turbulence characteristics were worked out at the Institute of Experimental Meteorology and reported in several papers [7, 8]. Since we were interested in diffusion in the direction across the mean wind, the analysis necessitated the use of the kinetic energy of the transverse component $\overline{v^2}$ of wind velocity fluctuations, which was not measured directly.

It is well known that in the surface layer, $\overline{u^2}$ and $\overline{v^2}$ are linearly related to the square of the dynamic friction velocity $v_*^2$. The numerical coefficients of this relation were obtained in a whole series of experimental studies and correlated in [9]. According to [9], it may be considered that on the average, the transverse component amounts to 3/4 of the longitudinal component. This made it possible to estimate $\overline{v^2}$ from the available $\overline{u^2}$ values.

The turbulent characteristics of $\overline{v^2}$ and $\varepsilon$ were used in an analysis of experimental results to carry out the normalization, which made it possible to reduce the results of different experiments to a comparable form. The normalization factor for the time of action of the source T and time of flight of the impurity t was the Lagrangian time scale of turbulence $\tau_L$ in the direction across the mean wind, a scale defined in terms of the available turbulence characteristics by the formula

$$\tau_L = \frac{\overline{v^2}}{c_1 \varepsilon}, \tag{4}$$

where $c_1$ is a constant taken as 0.6; the dispersions $\sigma_b^2$ and $\sigma_1^2$ were normalized to the square of the linear Lagrangian scale $r_L^2 = \overline{v^2}\tau_L^2$.

The turbulence characteristics of the atmosphere were measured on a series of levels of the high-level meteorological mast, and the normalization factors $\tau_L$ and $r_L$ were calculated by using the quantities $\overline{v^2}$ and $\varepsilon$ (average in the layer of propagation), the numerical values of which were obtained as weighted averages over vertical profiles $\overline{v^2}(z)$ and $\varepsilon(z)$.

Some basic characteristics of the series of experiments are shown in Table 2.

Table 2

| Series | Number of Paired Experiments | Height of Source, m | Time of Action of Source, $T$, min | $\tau_L$, sec | Limits of Distances (m) Up to Which $\sigma^2$ and $\sigma^2$ were Measured |
|---|---|---|---|---|---|
| 1 | 4 | 25–50 | 1,0–30,0 | | 1000–1300 |
| 2 | 12 | 25–50 | 1,0–45,0 | 50–250 | 1000–2000 |
| 3 | 6 | 2 | 0,5–10,0 | 20–200 | 100–200 |
| 4 | 4 | 73–100 | 2,0–50,0 | 100–450 | 1000–2500 |

A substantial drawback of experiments of series 1 (1963) is the lack of structural measurements of wind velocity fluctuations, which made it impossible to carry out the necessary normalization of experimental data.

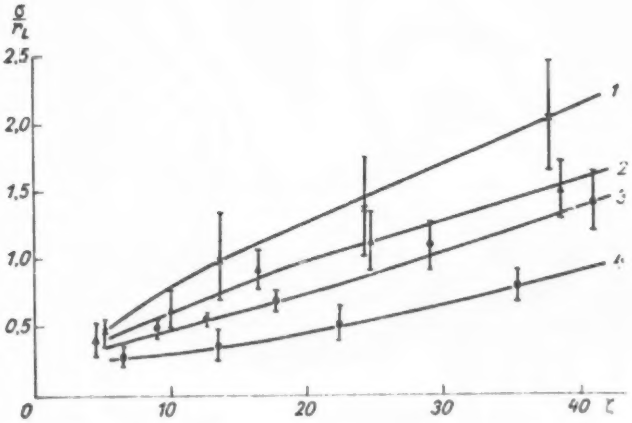

Fig. 2. Experimentally obtained variation of standard deviation $\sigma/r_L$ with diffusion time $\xi$.

1) $\eta > 10{,}0$; 2) $\eta = 3{,}5$; 3) $\eta = 1{,}5$, 4) $\eta = 0{,}75$.

Fig. 2 shows results of 30 experiments conducted in the summer of 1966 and 1967. The state of atmospheric stability was close to indifferent or unstable, and the height of the impurity source in the experiments ranged from 25 to 100 m. Values of $\sigma/r_L$ are laid off along the ordinate axis, and the normalized diffusion time $\xi = t/\tau_L$, along the abscissa axis; the curves were drawn through the experimental points for different times of action of the source $\eta = T/\tau_L$. Most justified statistically is the upper curve 1, drawn by averaging the results of 15 experiments. A considerable scatter of the experimental points is observed in this case, but it is within the limits of combined accuracy of determination of the dispersions (the accuracy of determination of $\sigma$ in the experiments was 10-15% [2]) and normalization factors. In this group of experiments, $\eta$ varied from 11 to 40, and an attempt to separate them in more detail according to $\eta$ failed to give any satisfactory results. Curves 2 and 3 were drawn by averaging three experiments. The scatter of the experimental points did not exceed ±25% in either case. Curve 4 was obtained by averaging the results of nine experiments, and the scatter of the points did not exceed ±15%.

Fig. 3 correlates the experimental results of 12 experiments conducted in the winter of 1967. A distinguishing characteristic of this series of experiments was the low height of the source (March 2, above a snow cover), and therefore the distances at which the dispersion of the transverse distribution of the density of the impurity deposit was measured were smaller. The same quantities as in Fig. 2 were laid off along the coordinate axes.

According to the time of action of the source, the experiments were divided into three groups; curve a was drawn by averaging six experiments, and curves b and c connect three experiments each. For comparison, Fig. 3 also represents a plot of the initial portion of the curves from Fig. 2.

Considering the accuracy of the experimental data, the agreement may be regarded as satisfactory. However, it should be noted that in the winter series of experiments, the normalized values of the dispersions are systematically slightly higher than in the preceding series. This may be due to certain operational differences in the experiments, inhomogeneity of the surface atmospheric layer, or characteristics of measurement of the normalization factors.

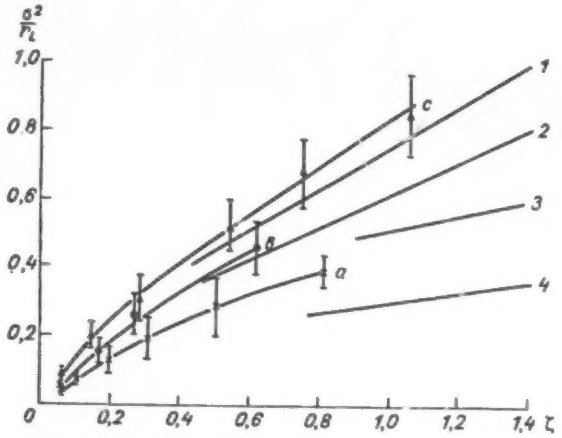

Fig. 3. Experimentally obtained dependence of standard deviation $\sigma/r_L$ on diffusion time $\xi$.

a) $\eta<1.0$; b) $\eta=2.5$; c) $\eta=8.0$; 1, 2, 3, 4 — см. Fig. 2.

The experimental curves shown in Figs. 2 and 3 make it possible to evaluate the width of the pollution zone ($2\sigma$) as a function of a high-level point source of impurity, taking the duration of its action into account. As already stated, this problem is analogous to the problem of determining the width of a pollution zone from a continuously acting source, allowing for the finiteness of the observation interval. The accuracy of such an estimate amounts to an average of ±25-30%. Considering the insufficient theoretical treatment of the problem of influence of averaging time on turbulent diffusion, a problem that is of decisive importance in evaluating the relationship between the average concentration during a given time interval and the maximum possible concentration of a pollutant in the atmosphere, the empirical relationships obtained are of definite practical interest.

Fig. 4 shows on a log-log scale the dependence of the ratio $\sigma_1/\sigma_b$ on the ratio of the times of action of a long and a brief source $T_1/T_b$, obtained from our experimental data. It follows from the graph that

$$\frac{\sigma_1}{\sigma_b} \sim \left(\frac{T_1}{T_b}\right)^{0,2}. \qquad (5)$$

On the basis of (5) and also by considering (1), (2) and (3), we can see that the decrease in the maximum density of the deposit with increasing duration of action of the source may be different depending on how active a part is played by vertical diffusion in this process. If its contribution is small and relation (1) applies, then

$$P_{\max} \sim T^{-1/5}.$$

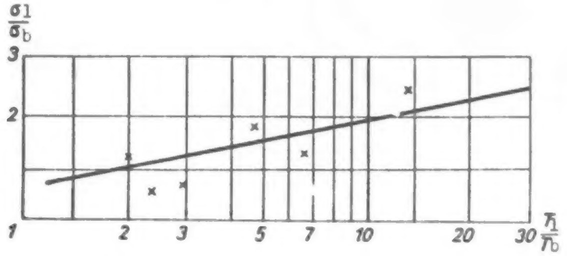

Fig. 4. Increase in width of pollution zone with increasing time of action of high-level point source.

In the other limiting case, when relation (2) may be considered valid,

$$P_{\max} \sim T^{-2/5}.$$

Three basic conclusions may be drawn from the above study:

1. The expansion of the pollution zone observed during increasing duration of action of a high-level point source and the resulting decrease in the axial densities of the deposit were quantitatively estimated. On the average, for the case of isotropic turbulent diffusion, the following relation is confirmed:

$$\frac{\sigma_b^2}{\sigma_1^2} \leqslant \frac{P_b}{P_1} \leqslant \frac{\sigma_b}{\sigma_1}.$$

2. An empirical dependence of the width of the pollution zone on the duration of action of a high-level point source was obtained.

3. The variation of the time-averaged axial density of the impurity deposit was found to be inversely proportional to the averaging time T to a power ranging from 0.2 to 0.4.

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*JU. S. OSIPOV*

## DIFFUSION FROM POINT SOURCE OF FINITE OPERATING TIME*

The question of dependence of density distribution of pollutant deposit on the ground surface in direction lateral to average wind upon the duration of elevated point source operation is considered. The results of some series of model experiments are analyzed in which sources of different operating time were used simultaneously. It is received that the dispersion of lateral pollutant distribution is growing with the increase of duration of source operation, and axial deposit densities are decreasing. Experimental results are presented in normalized form and generalized in some empirical curves depending on duration of source operation.

Under some suggestions, the problem of influence of finiteness of source operating time on pollutant distribution is analogous to the problem of influence of observation interval finiteness with continuously operating source. With this, the ratio evaluation of maximum possible and mean pollution concentrations for one or another period of time is of great practical interest. The obtained experimental results can serve for carrying out such evaluation.

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* Editor's note: The abstract is presented as given in English with the original Russian article.

# USE OF SURFACE OBSERVATIONS FOR CHARACTERIZING THE STATE OF THE SURFACE ATMOSPHERIC LAYER

G. B. Mashkova (USSR)

From Glavnoe Upravlenie Gidrometeorologicheskoy Sluzhby Pri Sovete Ministrov SSSR. (Chief Administration of the Hydrometeorological Service Under the Council of Ministers of the USSR.) "Meteorologisheskie Aspekty Zagryazneniya Atmosfery". (Meteorological Aspects of Air Pollution.) Sbornik dok'adov na mezhdunarodnom simpoziume v Leningrade - Iyul' 1968 g. (Reports delivered at the International Symposium in Leningrad - July 1968.) Pod redaktsiey d-ra fiz.-mat. nauk M. E. Berlyanda. (Edited by Prof. M. E. Berlyand.) Gidrometeorolgicheskoe izdatel'stvo, Leningrad, p. 215-220, (1971). (Hydrometeorological Publishing House, Leningrad, (1971).)

The stratification of the surface air layer plays an essential part in the determination of the capacity of the atmosphere to scatter noxious industrial emissions [1].

In the absence of an elevated inversion, lapse rate observations to a height of 10 m provide reasonably good information on the stratification of the entire surface layer. However, there are few points of lapse rate observations. For this reason, surface meteorological measurements assume a considerable importance. If the accuracy requirements for the determination of stratification are not very rigorous, Pasquill's classification can be used for conversion to characteristics of the state of stratification. However, this classification requires comparison with lapse rate observations.

The object of the present study was to draw such a comparison with materials of observations from the high-level mast of the Institute of Experimental Meteorology (lapse rate observations up to 8 m, weather station data, profiles in the 300 meter layer). Pasquill's classification based on the use of weather station data was compared with a classification based on the stability criterion $B \sim \frac{\Delta t}{v^2}$ in the surface layer, where $\Delta t$ is the temperature difference at heights of 4 and 1 m and v is the wind velocity at a height of 2 m.

Based on 1967 data, the frequency of different types of stability was calculated after Pasquill on the basis of fixed times for each individual month. Examples of the daily variation of different types of stability for January, April and July are given in Fig. 1. The times of sunrise and sunset are indicated by arrows.

Fig. 1 shows that in winter, an indifferent state prevails in the course of 24 hours, being twice as frequent during the day as at night. At night, a slight and moderate stability is observed rather frequently, but a marked stability is seldom observed. By spring, the number of 24-hour periods with a marked stability observed at night increases substantially, and an indifferent state is most characteristic of hours close to sunrise and sunset. In the daytime, the instability increases: the frequency of days with a slight instability increases markedly; days appear with a moderate instability, and near midday, with a marked instability. In summer, an indifferent state is observed mainly near sunrise and sunset, and somewhat less often near midday (the latter situation is apparently due to an increase in the quantity of cumulus clouds during these hours). The frequency of days with

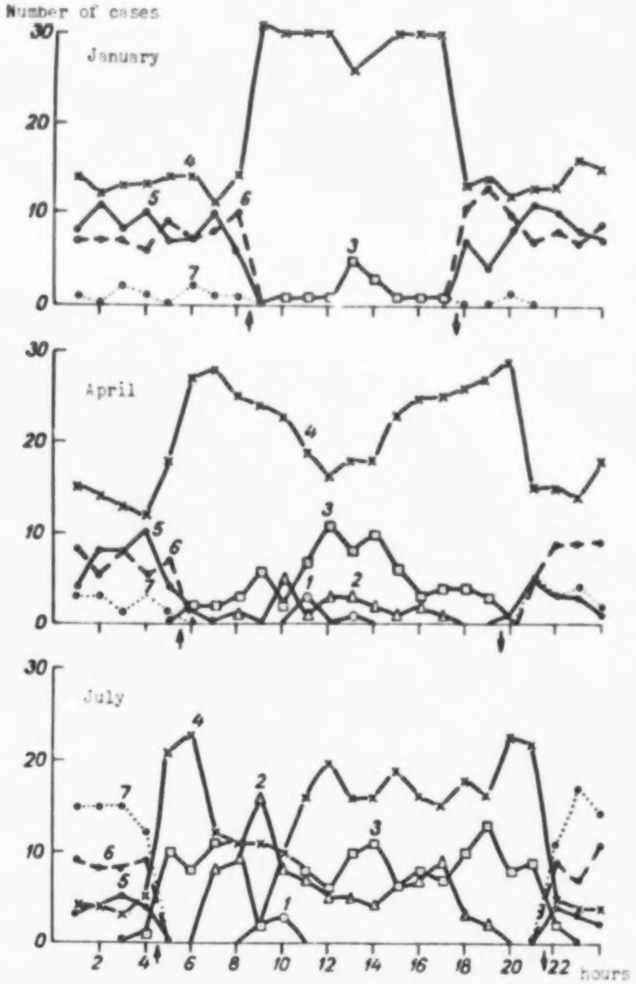


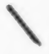
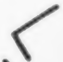
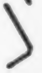
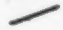
Fig. 1. Daily variation of different types of stability. 1 - very unstable state, 2 - unstable, 3 - slightly unstable, 4 - neutral (indifferent), 5 - slightly stable, 6 - stable, 7 - very stable.

a slight and moderate instability is almost as high as the number of days with an indifferent state. On some days, a marked instability is observed, most frequently during hours close to midday. At night, a marked or moderate stability prevails. In autumn, the picture gradually changes and comes to resemble that of spring (October is an almost complete analog of April).

All the observations for which the value of criterion B could be calculated were arbitrarily divided into groups according to the magnitude and sign of B (Tables 1 and 2). As one of the characteristics of these groups one can use the character of the temperature profile in the lower 300-meter layer as a function of the sign of the lapse rate in the 0.5-10.0 m layer and above [2].

Table 1

Frequency (%) of Temperature Profiles of Different Types According to Groups of Parameter B

| Type of Temperature Profile | Schematic Form of Temperature Profile | B | | | | | |
|---|---|---|---|---|---|---|---|
| | | $\leq -0.01$ | $-0.009, -0.002$ | $-0.001, +0.001$ | $0.002 - 0.009$ | $0.010 - 0.040$ | $\geq 0.050$ |
| | | Marked and Very Marked Instability | Slight and Moderate Instability | Indifferent State and One Close To It | Slight Stability | Moderate Stability | Marked Stability |
| 1 |  | 100 | 88 | 63 | — | — | — |
| 2 |  | — | 12 | 4 | — | — | — |
| 3 |  | — | — | 29 | 70 | 36 | — |
| 4 |  | — | — | 4 | 30 | 64 | 100 |

Type 1 assumes the presence of a vertical temperature lapse rate $\gamma$ in the entire 300 meter layer ($\gamma>0$); type 2, a positive lapse rate in the lower surface layer ($\gamma>0$) and a negative one above it ($\gamma<0$); type 3, a negative lapse rate in the lower surface layer ($\gamma<0$) and a positive one ($\gamma>0$) above this layer; type 4, stability ($\gamma<0$) in the whole (or nearly whole) 300-meter layer. The frequency of the different types of temperature profiles for different range groups of B are given in Table 1, compiled from observational material for several years in the warm half of the year. The table shows that in 33% of the cases, an indifferent state in the surface layer corresponds to temperature profiles with a changing sign of the lapse rate in the 300-meter layer (types 2, 3), i.e., corresponds to certain transition states in the layer considered, mainly in the morning and evening hours. A substantial portion of such profiles (70 and 36% respectively) are observed during a slight and moderate stability, and a much smaller portion (12%), during a slight instability. Examples of the temperature and wind velocity profiles for different values of B are given in Fig. 2.

Table 2

Frequency (%) of Different Types of Instability According to Groups of Parameter B

| Types of Instability Based on Surface Data | B | | | | | | |
|---|---|---|---|---|---|---|---|
| | ⩽−0,04 | −0,030, −0,010 | −0,009, −0,002 | −0,001, +0,001 | 0.002—0,009 | 0,01—0,040 | ⩾0,050 |
| | Very Marked Instability (1) | Marked Instability (2) | Slight and Moderate Instability (3) | Close to Indifferent State (4) | Slight Stability (5) | Moderate Stability (6) | Marked Stability (7) |
| 1 | 100 | — | — | — | — | — | — |
| 2 | — | 48 | 6 | 3 | — | — | — |
| 3 | — | 20 | 24 | 6 | 10 | 12 | 15 |
| 4 | — | 32 | 70 | 81 | 51 | 24 | 20 |
| 5 | — | — | — | 9 | 27 | 11 | 10 |
| 6 | — | — | — | 1 | 12 | 53 | 15 |
| 7 | — | — | — | — | — | — | 40 |
| Number of cases | 11 | 59 | 54 | 105 | 49 | 34 | 20 |

Table 2 gives the frequency of different types of stability after Pasquill (surface observations) according to groups of parameter B (lapse rate observations). As is evident from the table, the Pasquill types are in most cases similar to the types based on criterion B. The maximum frequency in five cases falls on the same type; in two other cases, on neighboring types. The latter situation is due to transition moments in the morning and evening periods, when a rearrangement of the stratification of the entire lower portion of the boundary layer takes place. For a very strong instability corresponding to the first type according to surface observations, we were unable to obtain a single value of B, since this type is characterized by a very low wind velocity at the wind vane, corresponding to a calm at a height of 2 m, so that B cannot be calculated. However, it follows from the same consideration that B under these conditions is much larger than 0.03 in absolute value, and hence, the first instability group according to B corresponds to the first instability group according to surface data.

Table 2 summarizes all the data obtained for the spring of 1967. Analysis of these data with separation into observations in the warm season (208 cases) and cold season (124 cases) gave a picture that was no different from the distribution of frequency according to types for the year. The only characteristic feature of the distribution was the fact that the number of cases of marked instability and marked stability in the cold half of the year was much lower than in the warm half, and the number of cases with slight and moderate stability was greater (as can be seen from Fig. 1).

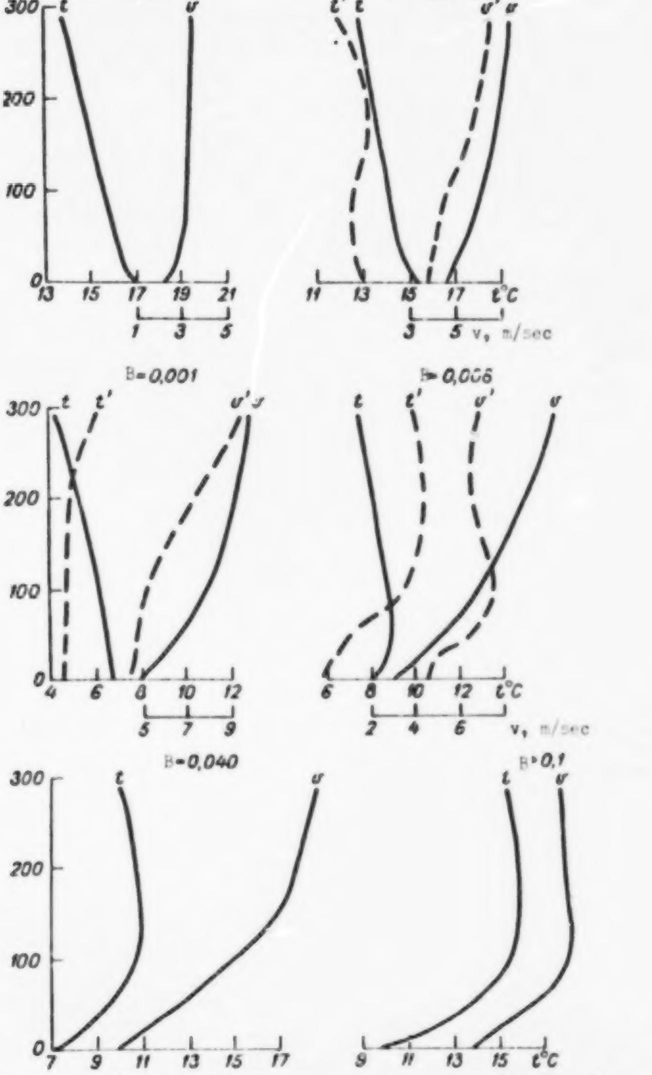


Fig. 2. Examples of profiles of temperature t and wind velocity v for different values of parameter B.

Thus, experience in comparing the two classifications, based on observations of an individual year, shows that the classification based on standard surface meteorological observations is apparently reduced to the classification based on lapse rate observations. Consequently, the characteristics obtainable with the aid of lapse rate observations may be justifiably extended to much larger areas when network meteorological observations are taken into consideration.

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## ON APPLICATION OF SURFACE OBSERVATION DATA TO STRATIFICATION CHARACTERISTIC OF LOWER PART OF BOUNDARY LAYER*

The possibility of employment of meteorological network observations for instability characteristic of lower part of boundary layer was studied. The comparison of stability types was carried out on Pasquill classification with instability parameter calculated on gradient observations. The frequency of different stratification types for seasons and during the day was shown on observation materials of 1967. Obtained data allowed to draw a conclusion on possibility of stratification characteristic distribution on large territories, taking into account the network observations.

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* Editor's note: The abstract is presented as given in English with the original Russian article.

# SULFUR DIOXIDE AND DUST MEASUREMENTS IN MEASURING NETWORKS OF THE HYDROMETEOROLOGICAL INSTITUTE*

O. Müller CSSR (Czechoslovak Socialist Republic)

From Glavnoe Upravlenie Gidrometeorologicheskoy Sluzhby Pri Sovete Ministrov SSSR. (Chief Administration of the Hydrometeorological Service Under the Council of Ministers of the USSR.) "Meteorologisheskie Aspekty Zagryazneniya Atmosfery". (Meteorological Aspects of Air Pollution.) Sbornik dokladov na mezhdunarodnom simpoziume v Leningrade - Iyul' 1968 g. (Reports delivered at the International Symposium in Leningrad - July 1968.) Pod redaktsiey d-ra fiz.-mat. nauk M. E. Berlyanda. (Edited by Prof. M. E. Berlyand.) Gidrometeorolgicheskoe izdatel'stvo, Leningrad, p. 221-226, (1971). (Hydrometeorological Publishing House, Leningrad, (1971).)

In most industrial countries, a significant increase in air pollution has been recorded in recent years.

Czechoslovakia, too, has not been spared from the negative results of industrialization. In particular, the bad effects of air pollution have today become an economic and sociological problem of the first rank. Some areas are even today limited in their further industrial development by the air pollution factor. At present, unfavorable air purity conditions prevail in the North Bohemian coal basin, one of the greatest regions of industrial concentration of our country. It is maintained that this area is one of the most polluted regions of the world. The origin of the air pollution is for the most part due to the burning of low-quality lignite produced in the North Bohemian open pit mines. It serves as the energy source for all the industry in the region. This lignite contains from 1.5 to 6% sulfur in its dry material. In combustion processes, this sulfur is mostly exhausted to the atmosphere as sulfur dioxide. The greatest $SO_2$ emitters in the region are large power plants, which are assigned the greatest proportion of the air pollution.

Also of decisive importance in the pollution of the air layers near the ground are industry, house fires, steam-powered transporation, and burning coal seams.

The danger of very high air pollutant concentrations is due to the unfavorable meteorological situation of the North Bohemian basin. This region, covering an area of about 3,500 $km^2$, is bounded on the northwest by the Erzgebirg chain and on the southeast by the offshoots of the Central Bohemian Range. It is a poorly ventilated area, in which weather conditions with poor exchange frequently occur, leading to accumulation of injurious materials.

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* Editor's note: This report was originally presented in German. Its English translation has been supplied by APTIC.

Results of air pollution include, among others, extended forest damages, decreased yields in agricultural production, and increased corrosion damage. But it is mostly the population which must suffer from the air pollution. Aside from stress due to dust and smoke, suspicious differences in the state of health of population groups from industrial cities and from regions without industry have been related to air pollution.

The extensive reports available on the bad effects of polluted air on humans, animals, plants, and economic goods are so far contrasted to only occasional exact data on the concentrations of harmful materials in the air. But the measurements undertaken have shown that the maximum immission concentration values for $SO_2$ are far exceeded in many places.

In the last few years, the hygienic service has performed long-term and large-scale measurements of sulfur dioxide and dust in the North Bohemian basin by means of semiquantitative methods. Thus $SO_2$ has for several years been determined by a summation method based on spontaneous absorption of $SO_2$ in a sodium hydroxide solution. To be sure, the absorption rate is strongly dependent on the wind velocity and the temperature. The method provides relative values which are quite comparable with each other, but which do not allow direct conversion into $SO_2$ concentrations. At present, this measuring network includes some 300 test points.

At the same test sites, the dust deposition is determined by a sedimentation method. Amounts of dust deposited in collection vessels are determined gravimetrically every month. This method also provides only approximate values, as it is well known that the larger particles of airborne dust predominate by far and so are determined preferentially.

In 1967 the Hydrometeorological Institute of the CSSR was given the mission of establishing a measuring network for measurement of sulfur dioxide and dust concentration in the North Bohemian coal basin. The goal of this research can be summarized briefly in the following points:

1. The experimental values are to provide information on the present state and further development of air pollution.
2. The $SO_2$ and dust concentration values determined, along with meteorologic measurements, are to serve as bases for study of the relations between air pollution, weather, and climate.

The practical application of the measurements lies primarily in the following areas:

1. The values determined for $SO_2$ and dust concentration serve as bases for remedial measures.
2. The effectiveness of the measures carried out for decreasing emissions will be evaluated by means of the measurements.
3. The concentration values will be bases for the evaluation of sites for possible construction of more large emitters, especially power plants.
4. The measurements will be made available to all institutions directly interested in air pollution.

Determination of the relation between air pollution, weather and climate should contribute to knowledge about the dissemination of harmful material in the boundary layer, serve to make diffusion calculations more precise, and finally, contribute to the possibility of air pollution prognosis, which would be in the form of a warning service for the controlled operation of large emitters of the greatest importance.

About 85 fixed long-term measuring sites are planned in the whole region covering some 3,500 $dm^2$. The measuring points do not form a geometric network. Rather, they are selected so that the basin proper as well as the slopes and ridges of the Erzgebirge range are rather evenly covered by measuring sites. To exclude local effects on the measurement as much as possible, and to obtain a larger range of representative values, we attempted to set up measuring sites away from the larger settlements and industrial plants. In following the level of harmful material in a large area measurement area, we cannot go into the often more complex air pollution conditions in settlements or on factory land. Thus only some control measuring points are planned in cities.

As already mentioned, the measuring program proper is limited to measurement of concentrations of $SO_2$ and dust.

At all the measuring sites, the sampling period for $SO_2$ and dust is 24 hours. For about 10% of the measuring sites, a special program is planned, by which the time variability of the dust and $SO_2$ concentration will be followed with continuously recording analyzers.

The basic method for sulfur dioxide is the generally well known colorimetric determination according to West and Gaeke. An absorption solution is aerated for 24 hours in an impinger washing bottle with a measured amount of outside air. The sulfur dioxide content of the air sample is then determined in the laboratory with a color reaction. The color resulting from the reaction is measured with a photometer. The intensity of the color is proportional to the $SO_2$ content of the sample.

To determine the dust concentration, a standardized membrane filter method recommended by the hygienic service is used. The amount of suspended dust caught on the filter is determined by weighing.

The automatic analyzers for sulfur dioxide and dust planned for the special measuring sites are both devices developed in the CSSR.

The sulfur dioxide trace analyzer developed by Novak works on the polarographic-coulometric principle. Reaction of the $SO_2$ with an absorption solution quantitatively produces a reaction product which is electrolytically decomposed in the device. The flow thus produced at an electrode pair is a measure of the $SO_2$ concentration in the air being studied. It is recorded continuously by a recorder. The recorder charts are evaluated over 30-minute intervals.

The Aerosol Concentrometer of Polydorova is used for continuous recording of dust concentration. The air under study is sucked through a continuously transported membrane filter tape. Following that, the decrease in the intensity of a light beam is measured. This is proportional to the blackening of the filter and thus to the dust concentration. Thirty-minute averages are taken from the continuous recording.

At the time, $SO_2$ experimental measurements are being done to a small extent. Routine measurements in the entire net will be started at the beginning of 1969. It should be mentioned that the $SO_2$ and dust orientation measurements of the hygienic service mentioned above are coordinated with the measuring program of the Hydrometeorological Institute. It is planned to perform all measurements at the same points.

After the description of the network for air pollution measurements, we shall briefly report on the meteorological companion measurements.

In this region, there are already available about 35 meteorological stations and two meteorological masts 80 m high. The program of the meteorological stations contains measurements of air temperature, relative humidity, and wind direction and velocity. The meteorologic masts have an extensive special program directed toward obtaining measuring values for a mesoclimatic evaluation of the limiting layer with respect to diffusion of harmful materials. Measurements and observations are carried out uninterruptedly on the masts, and evaluated at hourly intervals. At the same time, the masts are special measuring sites for measurement of harmful materials.

Less extensive measuring networks are planned for other industrial regions in the near future. Part of them are already under construction. These are the measuring networks in the districts of Frydlant (North Bohemia, with 12 measuring sites), Ostrava (North Moravia, about 25 measuring sites), Bratislava and Kosice (Slovakia, with a total of about 20 measuring sites).

For the next stage, we plan measurements of other harmful materials. We will be particularly concerned with the reaction products from $SO_2$. Sulfur dioxide is generally assigned the role of an indicator for air pollution by the waste gases from heating plants, but $SO_2$ is unstable. During its transport through the atmosphere it undergoes extensive physical and chemical reactions. It is obvious that the effect of weather conditions on oxidation should be followed, and the reaction products, such as total sulfur or sulfate, should be included in the measuring program.

## DETERMINATION OF CONCENTRATIONS OF SULFUR DIOXIDE AND DUST BY A MEASURING NETWORK OF THE HYDROMETEOROLOGICAL INSTITUTE* (ABSTRACT)

O. Müller (Czechoslovak Socialist Republic)

In recent years, the level of atmospheric pollution in Czechoslovakia has risen considerably. Particularly unfavorable conditions arose in one of the major industrial regions of the country, the North Bohemian coal basin, whose open pits are used to mine low-grade brown coal, which is the chief source of power for the industry in that region. The high sulfur content of brown coal (from 1.5 to 6%) causes considerable amounts of sulfur dioxide to be discharged into the atmosphere during the combustion of coal. Large sulfur dioxide concentrations in air persist for a long time as a result of the geographical characteristics of the location of the coal basin, which occupies a vast territory bordering on mountains where stagnant situations frequently arise.

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* This is a translation of the original Russian abstract accompanying this German paper.

In the last few years, Czechoslovakis's sanitary service conducted studies of air pollution over the territory of the coal basin, where a network of stations consisting of 300 points was created. This network performed measurements of mean daily sulfur dioxide concentrations and of dust deposits by using semiquantitative methods. The sulfur dioxide concentration was determined by the addition method, based on spontaneous adsorption of the gas in a solution of sodium hydroxide. Since the magnitude of the adsorption substantially depends on the wind speed and temperature, it is difficult to convert the relative values obtained to actual sulfur dioxide concentrations. The magnitude of the dust deposit was determined by a gravimetric method.

In 1967, a study of air pollution in the region of the North Bohemian coal basin was initiated by the Hydrometeorological Institute of CSSR, which organized a measuring network consisting of 85 stationary points located at a certain distance from major population centers and industrial plants. The program of studies involves measurement of mean daily concentration of sulfur dioxide and dust in air.

The West-Gaeke method is used to determine the sulfur dioxide concentration. The dust content is determined by means of membrane filters. Continuous monitoring of the sulfur dioxide and dust concentrations is carried out at 10% of the measuring points by means of automatic analyzers. A Novak gas analyzer based on the polarographic-coulometric principle is used to record sulfur dioxide. The dust concentration is recorded with a Poliderov aerosol concentrometer based on measurement of the attenuation of the intensity of a light beam passing through the moving belt of a membrane filter through which the air studied is drawn. The tracings obtained on the belts of the two analyzers are averaged over a 30-minute interval.

In the coal basin region, in addition to measurements of air pollution at 35 meteorological stations and two 80-meter meteorological towers, meteorological observations are carried out that include measurements of temperature and relative humidity of air and wind velocity and direction.

An expansion of the studies of atmospheric pollution is being contemplated in the immediate future. The creation of a network of measuring points in other industrial areas and an increase in the number of ingredients measured have been proposed.

# EXPERIMENTAL STUDIES OF ATMOSPHERIC POLLUTION IN INDUSTRIAL AREAS

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From Glavnoe Upravlenie Gidrometeorologicheskoy Sluzhby Pri Sovete Ministrov SSSR. (Chief Administration of the Hydrometeorological Service Under the Council of Ministers of the USSR.) "Meteorologisheskie Aspekty Zagryazneniya Atmosfery". (Meteorological Aspects of Air Pollution.) Sbornik dokladov na mezhdunarodnom simpoziume v Leningrade - Iyul' 1968 g. (Reports delivered at the International Symposium in Leningrad - July 1968.) Pod redaktsiey d-ra fiz.-mat. nauk M. E. Berlyanda. (Edited by Prof. M. E. Berlyand.) Gidrometeorolgicheskoe izdatel'stvo, Leningrad, p. 227-257, (1971). (Hydrometeorological Publishing House, Leningrad, (1971).)

An experimental study of the spreading of noxious substances from individual high sources and of the influence of meteorological conditions on the concentration field were begun by the A. I. Voyevkov Main Geophysical Observatory in collaboration with the Moscow Institute of Hygiene im. F. F. Erisman and other agencies in 1961. Since that time, extensive expeditions have been carried out every year in the areas of individual sources with different emission characteristics, in different seasons and in different climatic zones. The results obtained make it possible to draw a comparison with data of methods for calculating the scattering of impurities in the atmosphere and to establish the mechanism of propagation as a function of the meteorological conditions and emission parameters. They are also of great importance in the development of methods studying the pollution of a city's air reservoir as a whole.

In the study of the concentration field in the region of individual sources, an extensive series of measurements were formulated that include meteorological observations, the determination of the concentration field, and the measurement of emission parameters [3, 4, 7]. A distinctive feature of these studies is the fact that they involve the measurement of not only the concentrations of pollutants, but also of all the main elements determining the spreading of impurities under natural conditions.

A significant influence on the scattering of an impurity in the atmosphere is exerted by the distribution of the wind velocity, temperature, wind direction and other meteorological elements, the greatest variation of which in both height and time is observed in the surface layer. For this reason, the most detailed measurements were carried out in this layer (when the indicated expeditionary work was organized). The wind speed was measured at eight levels of a telescopic mast up to a height of 17 m by means of contact anemometers with recording on electromagnetic counters. This method made it possible to perform an automatic averaging of the wind speed over the necessary time and to carry out remote measurements.

In view of the fact that the duration of the sampling was 20 minutes, the wind speed was also averaged over 20 minutes, with subsequent averaging over 1 hour. The temperature and humidity of air were measured at six levels from 0.2 to 17 m with resistance thermometers, and measurements of the solar radiation were made with a balansometer, actinometer, and albedometer. The soil evaporation and temperature were measured at five levels to a depth of 20 cm. All the meteorological elements were recorded round the clock, every hour during the day, every 3 hours at night, and every hour during the sampling.

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Fig. 1. Telescopic masts with installed wind velocity and temperature gauges.

Fig. 1 shows 17-meter telescopic masts with wind velocity and temperature gauges.

The data obtained permit the calculation of the turbulence coefficient and the elimination of the influence of individual meteorological elements on the degree of atmospheric pollution. Continuous recording of the variation of wind direction by means of an anemorhumbograph permits an evaluation of the degree of dissolution of the plume in the horizontal plane.

The presence of a high stack through which the noxious pollutants are discharged into the atmosphere, a considerable exit velocity of gases from the stacks, and for hot sources, overheating of the gases relative to the ambient air leads to an effective ascent of the plume. Thus, for a high-capacity state regional electric power plant (SREPP) with a stack height of 120 m, the effective ascent is 30 to 200 m, and under certain meteorological conditions, as high as 1000 m. For this reason, it was important to determine the size of the plume in width at various distances from the source, the range of propagation of its visible portion, and the height of ascent. The measurements were made with the aid of an airplane or helicopter and by photographing in the plane perpendicular to the plume.

To measure the meteorological elements at heights up to 500 m, use was made of the balloon sounding method, and up to 1000-1500 m, of a specially equipped airplane or helicopter.

One of the main areas in the overall program of study consisted in determining the surface concentrations of a number of major pollutants. The most commonly employed chemical methods of analysis were used for this purpose with only slight modifications. The accuracy of most of these methods was 20%. Basically, the sampling for all gaseous ingredients was made by the suction method by drawing a given volume of air through an absorbing instrument.

The dust was collected by using filters of FPP-15 cloth, and the concentration was determined gravimetrically. The sensitivity of the determination of dust was 0.1 mg/m$^3$. The air, which was analyzed for the soot content, was drawn through paper filters. The soot concentration was determined from the degree of blackening of the filter, and the sensitivity of the determination was 0.1 mg/m$^3$.

Gases and substances in vapor form were trapped in liquid absorbing media. Absorbing instruments with a porous glass plate were used for this purpose. The sulfur dioxide concentration was determined by absorbing the gas in a potassium chlorate solution, then determining the sulfate ion formed by turbidimetry. The sensitivity of the method was 0.12 mg/m$^3$. Nitrogen dioxide was determined with Griess reagent after absorption in potassium iodide solution. The sensitivity of the determination was 0.02 mg/m$^3$. Carbon monoxide was determined by using a TG-5 gas analyzer in which the oxide was burned to the dioxide, then determined titrimetrically. The sensitivity of the determination was 1.5 mg/m$^3$. Carbon disulfide was determined from the reaction of formation of a colored compound, copper diethyldithiocarbamate. To eliminate the influence of hydrogen sulfide and sulfur dioxide, tubes filled with dry adsorbents were used. The sensitivity of the determination was 0.02 $g/m^3$. Phenol was determined from the reaction with diazotized paranitroaniline. The sensitivity was 0.01 $mg/m^3$. Hydrogen sulfide was trapped with a suspension of cadmium hydroxide and determined from the reaction of formation of methylene blue. The sensitivity of the method was 0.006 $mg/m^3$.

In the survey of individual high-output sources, the samples were collected under the plume at about 20 points simultaneously at 3-5 distances and sometimes more. At each distance, from 3 to 5 sampling points were established perpendicular to the plume at a distance of 50-400 m from one another depending on the width of the plume.

To determine the influence of the daily variation of meteorological elements on the scattering of the impurity, the sampling was carried out at different times of day: in the morning (in the presence of weakly developed convective exchange), during the day (during the period of maximum turbulent exchange) and in the evening (when the turbulent exchange had decreased).

Simultaneously with the sampling, a measurement was carried out on the characteristics of the emission, including the determination of the total volume of gases discharged and the amount of pollutants discharged for each ingredient and temperature of the escaping gases.

The collection and analysis of samples in cities with advanced industrial development have by now been organized. In order to study the pollution of the air reservoir of cities, stationary sampling points are being organized [2]. In many cities, samples are collected along a predetermined route by a specially equipped machine and under the plumes of the main sources.

The sampling points are located on open, well-aerated sites characteristic of a given district of the city, taking into account the location of the pollution sources, the wind rose, and as a rule, in places of maximum pollution. Due consideration was given to the fact that the concentration maximum is observed at a distance of 20 H from the source (H being the height of emission of the pollutants). Special booths were set up at the stationary sampling points (Fig. 2). This made it possible to obtain representative data and to carry out the sampling at any time of day, an important feature in determining the relationships between pollution and meteorological conditions.

Simultaneously with sampling at stationary and route points, observations were made on the speed and direction of the wind, temperature and humidity of air, and special weather phenomena and special conditions that might influence the magnitude of surface concentrations.

A general meteorological characterization of an air mass is obtained as a result of additional meteorological measurements (lapse rate observations, sounging of the atmosphere with the aid of a surface radiosonde at the nearest meteorological station).

The data obtained in a survey of one of the thermal power plants permit the establishment of several dependences on various meteorological elements [5]. Measurement of the emission characteristics made it possible to select for analysis cases in which the source operated stably, and thus, after the surface concentrations have been measured, the source is uniquely determined in this case by the meteorological conditions of the scattering.

In order to bring out the influence of the daily variation of meteorological elements on the scattering of pollutants, all the data were divided into three groups as functions of the sampling time: a morning period from 5 to 9 A.M., a daytime period from 9 A.M. to 4 P.M., and an evening period from 4 P.M. to 7 P.M. Fig. 3 shows curves enveloping the maximum sulfur dioxide concentrations at different distances from the source at different time of day. As is evident from the figure, the lowest concentrations are observed during the morning periods. On passing to daytime conditions, the zone of concentrations above the maximum permissible norm is quadrupled, and from the standpoint of the absolute maximum, more than doubled. During the evening period, a decrease of the concentrations is observed at all distances.

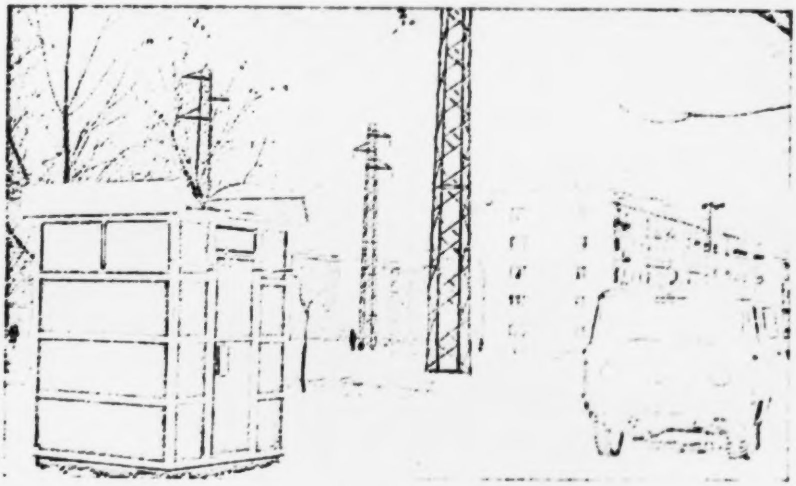

Fig. 2. Booth for collecting air samples.

Thus the most unfavorable conditions are created during the daylight hours, when the concentrations are considerably increased and the zone of pollution is substantially widened.

Such studies were carried out separately for conditions of anticyclonic, cyclonic and intermediate pressure fields. They gave similar results that may be explained by a variation in turbulent exchange, which increases from morning to daytime hours and decreases toward evening. This is in good agreement with the theoretical treatments developed at the Main Geophysical [1].

A strong influence on the variation of surface concentrations is exerted by various meteorological elements. Fig. 4 shows curves enveloping the maximum concentrations during the winter and summer periods as functions of

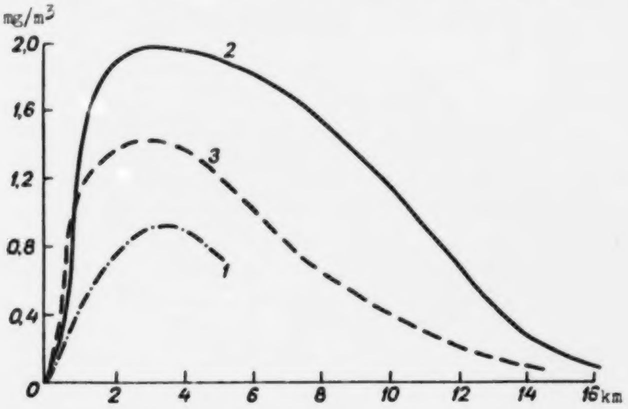

Fig. 3. Variation in sulfur dioxide concentrations under the plume of a high-output source.
1 - morning, 2 - day, 3 - evening

temperature $\Delta t$ in the 0.5-2 m layer (for $\Delta t \leqslant 0$ and $\Delta t > 0$). It is evident from the course of the curves that in the presence of an isothermal or inversion

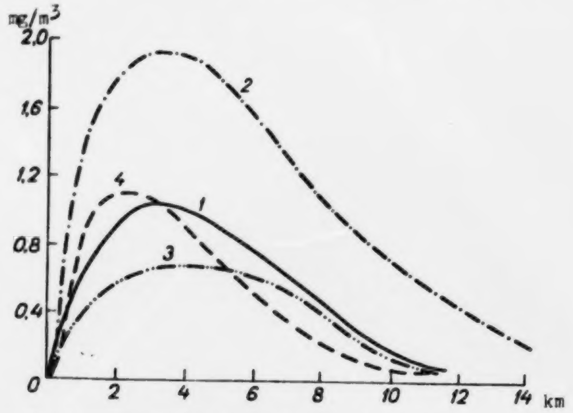

Fig. 4. Variation of sulfur dioxide concentrations in the region of a major source as a function of the temperature difference $\Delta t$ in the 0.5-2 m layer.
Summer: (1) $\Delta t \leqslant 0$, (2) $\Delta t > 0$; winter: (3) $\Delta t \leqslant 0$, (4) $\Delta t > 0$.

distribution of temperature, the surface concentrations of sulfur dioxide decrease substantially. Thus, when $\Delta t > 0$, they are approximately twice as large as when $\Delta t \leqslant 0$.

On passing from winter to summer conditions, a general increase in concentration and a 1.5-fold expansion of the range of influence of the source takes place.

An analogous graph was plotted for the distribution of maximum concentrations for different gradations of wind velocity at a height of 2 m above ground: 0-2 m/sec, 3-6 m/sec, and above 6 m/sec. It follows from this graph that the minimum sulfur dioxide concentrations are observed at a wind velocity up to 2 m/sec. There is no distinct maximum, the concentrations do not exceed the MPC, and are four times less than at wind velocities greater than 2 m/sec. As the wind velocity increases, the concentration near the ground is seen to increase. It reaches a maximum value of 1.8 mg/m$^3$ at a wind of 3.0-6.0 m/sec. As the wind velocity increases further, the absolute value maximum is preserved, but it shifts toward the source. This may be explained by the fact that at such velocities, the effective height of ascent of the plume is moderate, the plume is nearly horizontal, and as a result of vigorous mixing, the sulfur dioxide gas is rapidly carried toward the ground to form a concentration maximum near the source.

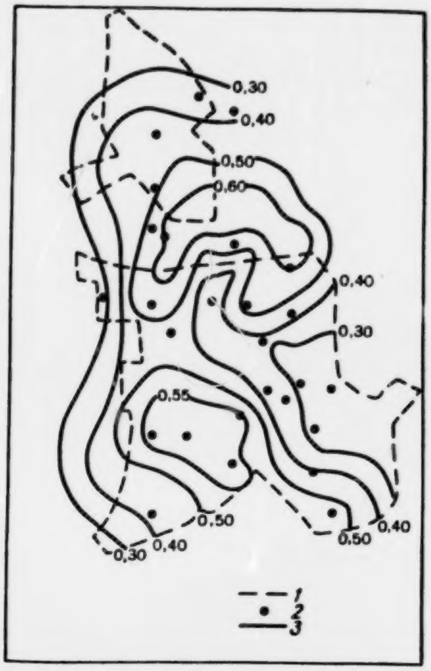

Fig. 5. Isolines of equal sulfur dioxide concentrations on the territory of a city.
1 - city limits, 2 - sampling points, 3 - isolines of mean monthly concentrations.

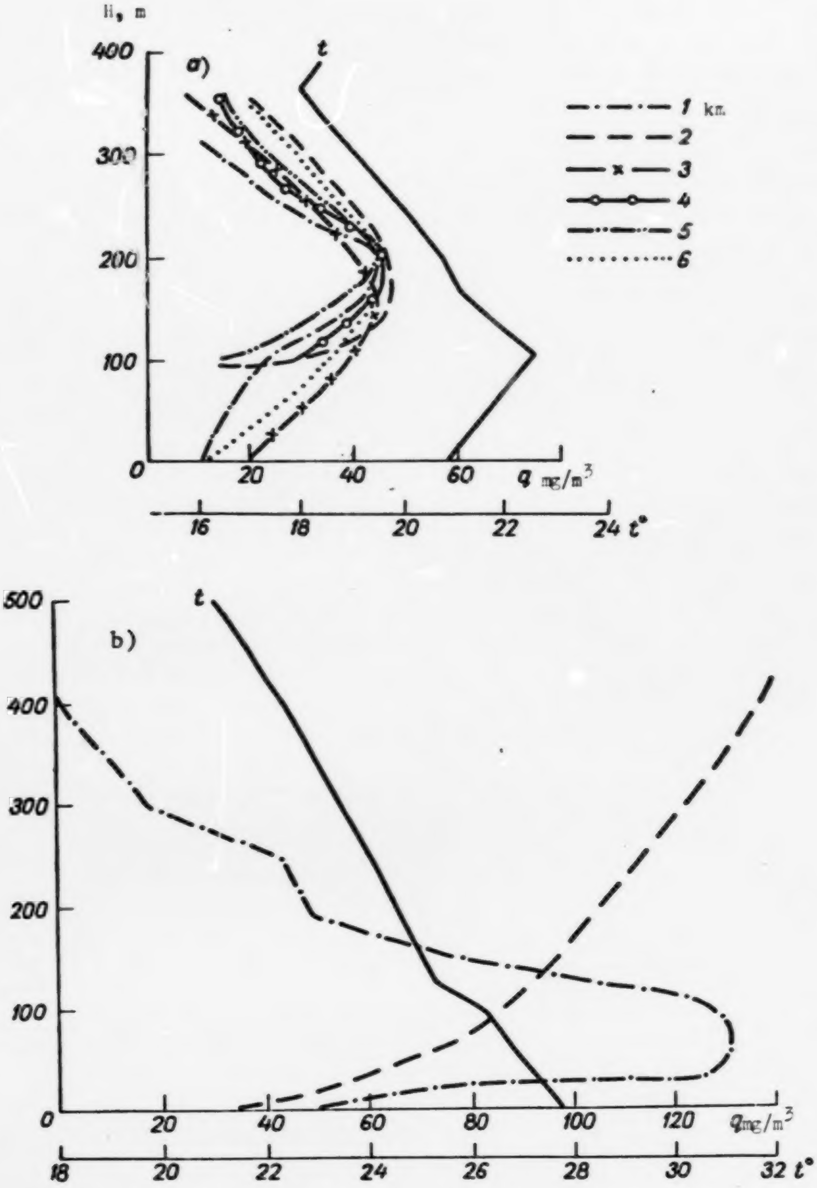

Fig. 6. Height distribution of carbon monoxide concentrations in the plume of a metallurgical plant for a stable (a) and unstable (b) stratification (t) at various distances from the source.

A different type of dependence on the wind velocity is observed for lower and smaller sources located in a city. Maximum sulfur dioxide concentrations near the ground are observed in these cases at wind velocities up to 4 m/sec. For high sources in the city, as the wind velocity increases, there is usually an intensification of turbulent mixing, which on the one hand leads to a more intensive transport of impurities into the lower atmospheric layer, and on the other hand, the atmosphere of the city becomes cleaner as a result of a stronger aeration of residential sections.

The turbulence coefficient was calculated from lapse-rate observation data. The data obtained were distributed over three gradations: 0-0.10, 0.11-0.20 and 0.21-0.3 $m^2$/sec. A graph analogous to the previous ones was plotted for these gradations. It showed that the magnitude of the concentrations in the surface layer strongly depends on the turbulence coefficient: the lower the latter, the smaller the sulfur dioxide concentration near the ground. For the first gradation, the concentration maximum is approximately one-half of the second, and one-third of the third. As the turbulence coefficient increases, so does the zone of high concentrations.

An adequate network of sampling points in a city makes it possible to use the data obtained to draw lines of equal mean annual sulfur dioxide concentrations to identify the areas of minimum and maximum pollution of the air reservoir, the variations in space and time, the influence of meteorological conditions on the degree of atmospheric pollution of the city, and also to solve hygienic problems, take active steps to reduce the emission of pollutants into the atmosphere, etc.

Fig. 5 shows air sampling points and gives isolines of equal concentrations plotted from observational data for a city.

Of great interest is the study of the distribution of noxious substances with height in plumes of high-output sources and above a city [6]. To obtain such characteristics, a helicopter equipped for sampling the main ingredients (dust, CO, $SO_2$, $NO_2$) was used at the Main Geophysical Observatory.

Fig. 6 shows an example of the distribution of carbon monoxide concentrations in a plume from a metallurgical complex and presents temperature profiles based on radiosonde data.

The data obtained for concentrations above a city at heights of 100-400 m and sometimes up to 1500 m showed that the concentration field is quite spotty and that extensive data will be needed for a statistical correlation of the spatial characteristics.

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## EXPERIMENTAL INVESTIGATION OF AIR POLLUTION IN INDUSTRIAL REGIONS*

At present, The Main Geophysical Observatory together with other institutions carries out a great quantity of experimental works on studying chemical air content under different meteorological conditions. They are performed in two directions: concentration field determination in the zone of action of the plume from powerful sources and pollution level estimation in the atmosphere of towns with highly developed industry. The works are carried on in different seasons, in different climatic zones, taking into account diurnal variations of meteorological elements.

From 1961, 2 or 3 expeditions are organized every year in the regions of large industrial sources differing in technology of industry and emission characteristics, respectively. At the fulfillment of above-mentioned works a broad complex of observations is carried out which includes:

(a) measurements of temperature, humidity, wind velocity up to 17 m, and thermal balance and observations of wind direction variations;

(b) aerological observations of meteorological element distribution with the height using a captive balloon up to 500m and an aircraft and/or a helicopter up to 1000m;

(c) sampling under the plume simultaneously in about 20 points at 10—20 km distances from the source;

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* Editor's note: The abstract is presented as given in English with the original Russian article.

(d) measurement of emission parameter — a total volume of effluent gases, the quantity of noxious substances for each ingredient emitted into the atmosphere, and temperature of effluent gases.

In the system of Hydrometeoservice works on investigation of air pollution by industrial emissions are performed in more than 100 towns by means of organizing stationary points for air sampling. Besides, in some towns specially equipped cars are used which take air samples along definite route and under the plumes of main sources of air pollution. For this purpose, methodics of concentration determination are introduced for most prevailing ingredients: $SO_2$, $NO_2$, $H_2S$, CO, $CH_2$, soot and dust. With this, observations of meteorological elements determining pollutant dispersion are carried out.

For estimation of pollutant distribution with height over a town and in plume of single sources, samples are taken on helicopters.

Obtained materials on air pollution permit to study surface concentration field in dependence on variation of meteorological elements such as wind velocity, temperature distribution with height, exchange coefficient, etc., and on this basis to examine theoretical calculations of air pollution dispersion and to find out zones of maximum pollution.

# FIELD STUDIES OF AIR POLLUTION IN THE AREA OF THE SKAWINA ELECTRIC POWER PLANT

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From Glavnoe Upravlenie Gidrometeorologicheskoy Sluzhby Pri Sovete Ministrov SSSR. (Chief Administration of the Hydrometeorological Service Under the Council of Ministers of the USSR.) "Meteorologisheskie Aspekty Zagryazneniya Atmosfery". (Meteorological Aspects of Air Pollution.) Sbornik dokladov na mezhdunarodnom simpoziume v Leningrade - Iyul' 1968 g. (Reports delivered at the International Symposium in Leningrad - July 1968.) Pod redaktsiey d-ra fiz.-mat. nauk M. E. Berlyanda. (Edited by Prof. M. E. Berlyand.) Gidrometeorolgicheskoe izdatel'stvo, Leningrad, p. 238-240, (1971). (Hydrometeorological Publishing House, Leningrad, (1971).)

In the south of Poland, in the area of the Skavine (Skawina) electric power plant, which has an output of 400 MW and is a major source of sulfur dioxide emissions, field studies were carried out as early as 1958-1959. However, because of the imperfection of the instruments at that time, it was not possible to obtain data on the sulfur dioxide content near the plant, and all that was done was to compare the smoke plume shapes for different meteorological conditions [1]. In 1961, the field measurements were resumed. From May to December, six series of complex meteorological measurements, observations of smoke plume shape and sulfur dioxide content were carried out by using a special method.

Measurements of sulfur dioxide concentrations and inclination of the smoke plume were made in accordance with Zielinski's project, and the remaining measurements, according to the author's. Measurements of sulfur dioxide content in the surface air layer were made by means of instruments mounted on two trucks. Whenever it was technically possible, the trucks drove under the smoke band and performed the measurements.

In view of the fact that at a certain distance from the power plant stack the smoke became invisible, the actual direction of the smoke plume and also its variation was reported by meteorologists stationed in the vicinity of the plant, either by radiotelephone or by radio transmitter. The meteorologists recorded the variations in direction of the smoke band in detail so that it was possible to represent on diagrams the directions of propagation of the smoke plume and the distances at which the sulfur dioxide concentration were measured, and also the time of the measurements. As a result, it was possible to compare the position of the trucks carrying the measuring instruments and the wind direction at the level of the stack orifice. Thanks to the use of trucks, daily measurements of sulfur dioxide were made in the direction of propagation of the smoke band, and thus not only average, but also instantaneous values of sulfur dioxide concentration were obtained.

Measurements of surface concentrations of sulfur dioxide were carried out at two mobile measuring points by using EEL-$SO_2$METER British analyzers, which carried out continuous measurements [3]. These analyzers operate on the photocolorimetric principle by measuring the potential difference at two photoelectric cells caused by streams of iodine-starch solution flowing in front of them, one of the streams being partially formed when the solution comes in contact with atmospheric air containing sulfur dioxide and being sucked in. The lower sensitivity limit is around 0.03 mg/m$^3$; the time lag of the method is 2-2.5 min. Let us note that on the diagrams, the sulfur dioxide concentrations obtained are sometimes negative. This is due to the influence of oxidants present in air on the solution.

It was established experimentally [3] that air does not contain a sufficient amount of sulfur dioxide that could be measured by the method used in cases where the point of measurement is located at a certain distance from the plume axis. For this reason, if it was impossible to drive up in the truck directly under the plume, no sulfur dioxide observations were made on such days, so that only about 75% of the days could be used for the analysis.

The meteorological observations included: pilot balloon measurements of the wind to a height of about 500 m at a pilot balloon ascent velocity of 100 m/min, measurements of temperature and humidity of air with an aspiration psychrometer, observations of the state of weather (clouds, visibility, atmospheric phenomena) and shapes of the smoke plume, chiefly sketches, photographs and determination of the ascent height of the plume above the stack and its inclination.

In the final determination of the influence of meteorological conditions on the spreading of sulfur dioxide in the lower atmospheric layer, not only the results of observations and measurements in the area of Skawina, but also the results of meteorological analysis were taken into consideration: thermal stratification in the 1-2 kilometer layer of air, determined from radiosonde data at the nearest station, hourly description of the state of weather at the nearest synoptic station, and weather maps.

Observations of the ascent and inclination of the smoke plume were made from a position approximately perpendicular to the actual direction of propagation of smoke and located at a distance of 800 m from the plume. The measurements were made with Zielinski's instrument [3], consisting of a mirror photographic camera with a scale of angles and heights marked on the ground glass. The camera was mounted on a special tripod head that made it possible to rotate the camera along the vertical axis and also to adjust it relative to the horizontal by means of micrometer-type screws. A fixed lower section of the camera simultaneously took pictures of the smoke band. The angles and heights were read off directly from the image of the plume on the ground glass by using the scales marked on it. The measurements were made every 5-10 minutes. At the same time, outlines of the smoke plume were drawn and photographed at half-hourly average intervals.

Measurements of the actual height at which the spreading of smoke in the atmosphere took place showed that it was highly variable. In most cases, from a practical standpoint, there was no natural increase in the effective stack height. Since the direction of the smoke plume immediately after it leaves the stack coincides with the direction of the resultant vertical smoke velocity and wind velocity at the exit from the stack, it could be postulated that the absence of a smoke ascent was due to significant wind velocities at the stack orifice. Table 1 confirms the validity of these assumptions. It was found that a marked plume ascent was observed only in certain ranges of wind velocity at the level of the stack orifice.

Table 1

| Wind Velocity at Stack Orifice, m/sec | Number of Cases | |
|---|---|---|
| | Presence of Ascent | Absence of Ascent |
| 0 | 8 | 0 |
| 1—2 | 6 | 2 |
| 3—4 | 1 | 8 |
| 5—10 | 0 | 6 |

The use of this simple and convenient method yielded results of theoretical and practical interest [2]. Moreover, this method makes it possible to draw by analogy a number of conclusions regarding other electric power plants in Poland, either those already in existence or those being planned.

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*V. PARCHEVSKY*

## FIELD INVESTIGATIONS OF AIR POLLUTION IN THE REGION OF POWER STATION IN SKAVINE*

Power station in Skavine with output of 400 MW is a powerful source of sulphur dioxide emission. Field investigations of emission distribution were carried out in 1961. Some results of these works are given. Observation complex included sulphur dioxide measurements. Sampling was carried out with the help of two cars which were situated directly under the plume at different distances from the stack during measurement period. Observations of plume form and rise included its photographing with one camera and sketching the form of the plume. Pilot-balloon observations and meteorological observations in surface air layer were carried out simultaneously in the station area. Analysis of materials allowed to find out wind velocity effect on the height of plume rise.

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* Editor's note: The abstract is presented as given in English with the original Russian article.

# EFFECT OF METEOROLOGICAL CONDITIONS ON AIR POLLUTION IN CITIES OF THE SOVIET UNION

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From Glavnoe Upravlenie Gidrometeorologicheskoy Sluzhby Pri Sovete Ministrov SSSR. (Chief Administration of the Hydrometeorological Service Under the Council of Ministers of the USSR.) "Meteorologisheskie Aspekty Zagryazneniya Atmosfery". (Meteorological Aspects of Air Pollution.) Sbornik dokladov na mezhdunarodnom simpoziume v Leningrade - Iyul' 1968 g. (Reports delivered at the International Symposium in Leningrad - July 1968.) Pod redaktsicy d-ra fiz.-mat. nauk M. E. Berlyanda. (Edited by Prof. M. E. Berlyand.) Gidrometeorologicheskoe izdatel'stvo, Leningrad, p. 241-252, (1971). (Hydrometeorological Publishing House, Leningrad, (1971).)

In studying the influence of meteorological conditions on air pollution at the A. I. Voyeykov Main Geophysical Observatory (MGO), particular attention is given to a statistical analysis of data from observations of impurity concentrations in air carried out in cities. The analysis is performed on data of regular observations of pollution over a network of points in the system of the Hydrometeorological Service. These observations are made on the concentrations of sulfur dioxide, nitrogen oxides, carbon monoxide, dust, soot and other impurities in air at different times of day.

Data from impurity concentration measurements and meteorological observations are tabulated. The elaborated form, same for all cities, specifies subsequent punching of the data directly from the tables, all the columns of which correspond exactly to the columns on a punched card. A punched card file has been collected and is being supplemented. The observational material is used to study the influence of meteorological conditions on air pollution.

The purpose of our study was to find the dependence of pollutant concentrations in air on the set of meteorological elements for specific emissions. In approaching the solution to this problem, it is expedient to determine the relationships between air pollution and various meteorological elements. This point has been discussed in several studies [8, 9 etc.]. Our studies broadly confirm the conclusions reached by other authors, and also contain some new results.

Depending on the wind velocity, two maxima of urban air pollution are observed: one in the presence of a relatively weak wind (0-1 m/sec) and one at 5-6 m/sec (Fig. 1). The first maximum is obviously due to emissions from low sources, and the second, to high sources, this being in accord with the conclusions of theoretical studies. At wind velocities of 2-3 m/sec, a relative decrease of the pollutant concentrations is observed. An increased pollution of urban air is observed in surface inversions. At the same time, elevated inversions, which limit the vertical mixing of impurities, also pose a danger to cities (Table 1).

Table 1

Ratio of Average Concentrations in Air in the Presence of Surface and Elevated Inversions and in Their Absence

| City | Pollutant | Stratification | |
|---|---|---|---|
| | | Surface Inversions | Elevated Inversions in Lower 3 km Layer |
| Alma-Ata | Sulfur Dioxide | 1,4 | 1,3 |
| | Nitrogen Oxide | 1,3 | 1,1 |
| Dushanbe | Sulfur Dioxide | 1,1 | 1,0 |
| | Nitrogen Oxide | 1,5 | 1,4 |
| Moscow | Dust | 1,4 | — |
| | Sulfur Dioxide | 1,1 | 1,3 |
| Tallin | Dust | 1,4 | 1,3 |
| | Carbon Monoxide | 1,6 | 1,5 |
| Tbilisi | Dust | 1,3 | 1,4 |
| | Soot | 1,9 | 1,8 |

The dependence of pollutant concentrations on the wind velocity is different in surface and elevated inversions (Fig. 2). When surface inversions are present, the basic air pollution maximum is observed at weak wind velocities (0-1 m/sec), and in the case of elevated inversions, at a wind of about 5 m/sec. The latter case, however, is due to the influence of elevated inversions on the pollution of air with high emissions at the dangerous wind velocity [3].

Precipitation purifies the air by removing the pollutants. After the latter have deposited, the urban air is comparatively pure for a period of time (Table 2).

Table 2

Frequency of Pollutant Concentrations After Precipitation Relative to Average Value (Leningrad)

| Pollutants | Time Between End of Precipitation and Collection of Samples, Hours | | |
|---|---|---|---|
| | 0–1 | 0–12 | > 12 |
| Dust | 0,29 | 0,77 | 1,30 |
| Sulfur Dioxide | 0,26 | 0,85 | 1,26 |

Table 3

Frequency (%) of Increased Pollutant Concentrations as a Function of Combination of Meteorological Parameters

| v, m/sec | $\Delta T°$ | |
|---|---|---|
| | $\leqslant 0$ | $>7$ |
| $<10$ | 27 | 10 |
| $\geqslant 10$ | 21 | 20 |

Precipitation decreases the background pollutant concentration in the city, produced outside the range of influence of industrial emissions.

No purification of air by precipitation is observed when the pollutants are carried directly from the sources.

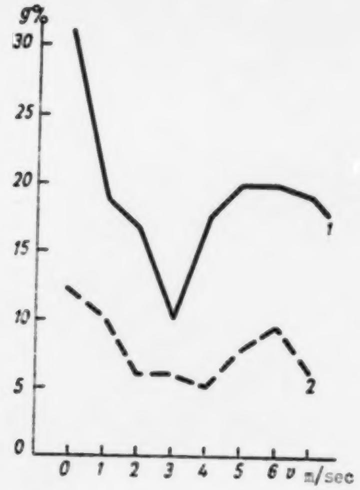

Fig. 1. Frequency of increased dust concentration in air as a function of wind velocity.

1 - Leningrad, 2 - Moscow

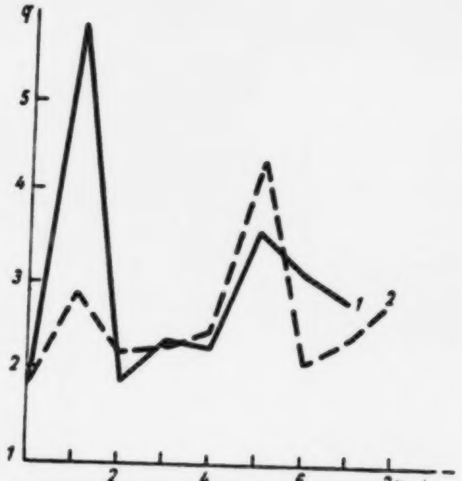

Fig. 2. Carbon monoxide concentrations in air as functions of wind velocity.

1 - surface inversion, 2 - elevated inversion

The complex influence of several meteorological factors on air pollution may be examined with the aid of synoptic situations reflecting the whole gamut of processes taking place in the atmosphere. However, an objective physical evaluation of the situations, given their considerable variability, presents some major difficulties. One can examine only the most distinct synoptic situations, which are comparatively stable in time. Of particular importance is the situation of a stationary anticyclone, associated with heavy air pollution in cities. An effective removal of pollutants from the air takes place in developed cyclones.

At the present time, a statistical method is being developed for objective consideration of the influence of a variety of meteorological parameters on air pollution. The method consists in using the initial meteorological parameters to separate the regions in multivariate space where similar magnitudes of air pollution concentrate. At first, from the group of parameters only those are selected which are statistically significant. Analysis of data from observations at one stationary point in Moscow revealed two statistically significant factors: $\Delta T$ -- the temperature difference between the 1 km level and the ground, and v -- the wind speed at the 1 km height. The first attempt to solve the problem in this manner failed to yield unambiguous results. However, it was possible to separate regions of different frequencies of high pollutant concentrations (Table 3).

It is evident from the table that the greatest probability of high pollutant concentrations is observed in an inversion associated with weak winds at the 1 km height. It is characteristic that in an unstable stratification, the frequency of high concentrations increases with increasing wind at the 1 km height. In the presence of a strong wind in the atmospheric boundary layer, the air pollution is practically independent of the stability.

The problem of a unique determination of the degree of air pollution on the basis of initial meteorological parameters may evidently be solved by substantially averaging the pollutant concentration values over space and time.

Analysis of the observational material showed that there is a tendency toward a simultaneous variation of air pollution in different parts of the city. Observational data on concentrations of nitrogen oxides and sulfur dioxide in air at seven stationary points in Sverdlovsk were used to calculate the space coefficient of the linear correlation between their values at different points. Fig. 3 shows the field of coefficients of correlation when the reference point was taken at the center of the city. It is evident from the figure that the isocorrelates are in the form of concentric circles, and the correlation gradually decreases with increasing distance from the reference point.

Based on material for 1967, a special analysis of periods of increased air pollution and corresponding meteorological conditions was carried out. An objective method was worked out for separating such periods. It consisted in the fact that the observational data for the individual stationary points for each pollutant were used to select a given number of cases with highest concentrations during a month, a season, or a longer period of time. The arbitrary criterion taken was a value of the concentration 1.5 times greater than the average concentration at the given point for a given pollutant. If in the course of a given period of time (one or several days), m is the number of cases of increased concentration and n is the total number of observations of the concentrations of all the measured pollutants at all the stationary points of the city during the given period of time, the degree of increased simultaneous air pollution in the city will be given by the quantity $P = \frac{m}{n}$, which ranges from 0 to 1.

Values of P were calculated for each day of January and July 1967 from data of observations of air pollution in a number of cities of the country. On the average, $P \approx 0.2$. For each city, we selected five days with the heaviest air pollution during a month. During these days, the P values were essentially 0.3-0.5, and climbed to 0.6-0.8 only during certain periods. Periods of

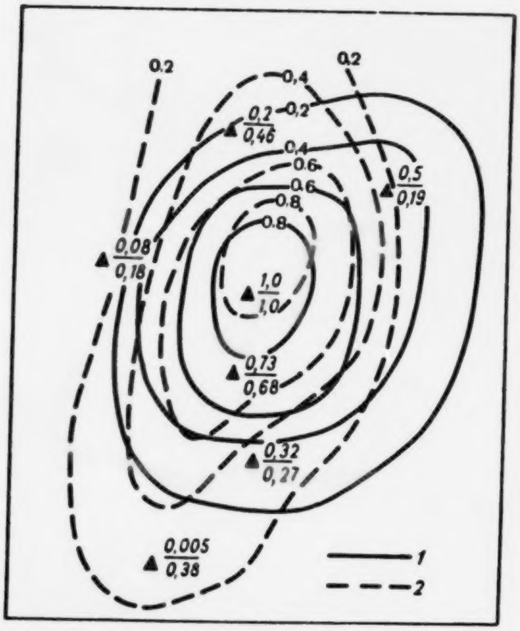

Fig. 3. Isocorrelates of pollutant concentrations in the city with the reference point at the center. 1 - nitrogen oxides (numerator), 2 - sulfur dioxide (denominator)

heaviest air pollution are observed most frequently in connection with the formation of stationary anticyclones. It is characteristic that a general increased air pollution was observed simultaneously in several cities located in the zone of a stationary anticyclone. Meteorological analysis of the separated periods requires a comparison of the meteorological parameters with the corresponding characteristics on days with reduced air pollution. Periods with a general reduction of air pollution are distinguished fairly easily, and their nonrandomness is demonstrated with the aid of statistical criteria. For each city, 5 days were selected with the lowest air pollution (smallest P values) in the course of a month.

In connection with the above, it was found convenient to distinguish three types of periods with different states of urban air pollution:

Type I - period of heavy general air pollution in the city, $P > 0.5$.

Type II - period of increased air pollution in the city with $P = 0.3$-$0.5$.

Type III - period of reduced air pollution in the city.

Averaged meteorological data during periods of increased and reduced air pollution are listed in Table 4.

Table 4

Average Characteristics of Meteorological Parameters for Different States of Air Pollution in Cities in 1967.

| Types of Period | January | | | | July | | | |
|---|---|---|---|---|---|---|---|---|
| | Wind Velocity, m/sec | | Cloudiness, Points | Difference of Temperatures Near the Ground and at 500 m Level in the Daytime | Wind Velocity, m/sec | | Cloudiness, Points | Difference of Temperatures Near the Ground and at 500 m Level in the Daytime |
| | Ground | 500 m Level | | | Ground | 500 m Level | | |
| I | 0,5 | 5,4 | 3,5 | −3,8 | — | — | — | — |
| II | 2,3 | 6,2 | 6,8 | −3,2 | 2,7 | 5,8 | 7,5 | 4,4 |
| III | 3,9 | 11,8 | 7,1 | +0,9 | 3,1 | 6,5 | 7,1 | 8,8 |

Analysis of Table 4 leads to the following conclusion: an increased air pollution in winter over a considerable territory of the city is simultaneously observed in the presence of a weak wind near the ground and at a level of 500 m, with a slight cloudiness and intense inversions persisting in the daytime. The combination of such conditions is characteristic of a stagnating air situation.

In the summertime, practically no periods of type I were observed. In July, there were no appreciable differences in wind velocity during periods of increased and reduced air pollution. The most distinct difference was found in the temperature lapse rate of the lower 500 meter layer; for a reduced air pollution, a pronounced air instability was observed.

On the whole, analysis of air pollution in different cities showed the presence of two clear-cut dangerous meteorological situations: stagnation of air, in which a simultaneous increase of pollutant concentrations is observed in different parts of the city, and a stable wind from the direction of the chief emission sources.

In most cities, the distribution of the air pollution sources over the territory is comparatively uniform, and here the greatest danger is posed by stagnation of air. In areas where a substantial number of industrial plants are concentrated in a given part of the city, both of the indicated situations are dangerous. Finally, there are many cities whose industrial plants are located beyond their boundaries. Obviously, a dangerous air pollution may be produced in this case only when the wind is directed from the plants toward the city.

In the near future, it will be necessary to develop a procedure for forecasting heavy air pollution. The usefulness of information on unfavorable meteorological conditions for the same day is most obvious when the industrial plants are located beyond the city limits and the increased content of noxious pollutants in the atmosphere is largely due to the wind direction. Initial experience is available on taking the weather conditions into consideration in order to prevent heavy air pollution without decreasing the production. When unfavorable wind directions are forecast, some industrial plants do not disconnect or repair their filters, and no forcing of the production is allowed.

The influence of meteorological conditions on air pollution manifests itself in the analysis of the annual variation of pollutant concentrations. Results of a comparison of the annual variation of many pollutants with corresponding variations of meteorological elements made it possible to establish a difference in the character of the influence of meteorological conditions on individual pollutants. The relationship of the annual variation of carbon monoxide and nitrogen oxides to the frequency of a wind velocity of 0-1 m/sec was identified most clearly (Fig. 4). This is due to the fact that an important producer of these pollutants is motor transport, which discharges its emissions almost at ground level. The annual variation of the dust concentration has its own characteristic features, since it is due not only to industrial emissions, but also to the natural dust content. The latter is an additional cause of increased dust pollution during the warm half of the year as compared with the cold half (Fig. 5).

The spring dust pollution maximum noted in [2, 6] is evidently determined not only by the increased frequency of anticyclonic circulation, but also by the state of the soil during that season. In many cities, an increase in sulfur dioxide concentration during the cold half of the year is observed as a result of increased fuel combustion (Fig. 6a). At the same time, in major industrial centers there takes place a summer maximum of the sulfur dioxide content of air in the presence of increased turbulent exchange (Fig. 6b).

In order to identify the regions with the most unfavorable climatic conditions conducive to accumulation of pollutants in air, it is necessary to evaluate the air pollution potential. Such a potential represents a combination of weather conditions determining the possible air pollution level. A frequent combination of meteorological conditions conducive to accumulation of pollutants in the surface layer indicates a high air pollution potential. A low potential exists in areas with a high frequency of meteorological conditions unfavorable to the creation of high surface concentrations.

The chief meteorological factors used for estimating the air pollution potential are determined by their influence on the process of transport and scattering of pollutants (velocity and direction of wind, vertical thermal stratification characteristic, fogs), on the regulation of the amount of consumed fuel (temperature of air), removal of pollutants from the atmosphere (precipitation), formation of photochemical smog (solar radiation), etc.

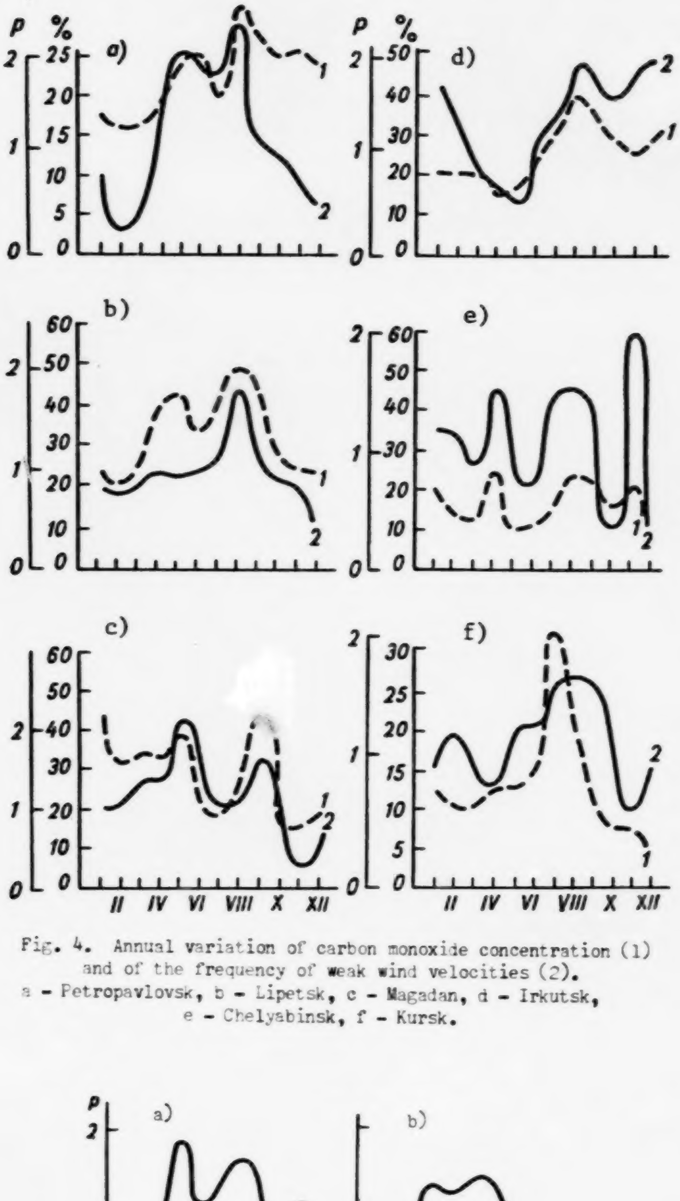

Fig. 4. Annual variation of carbon monoxide concentration (1) and of the frequency of weak wind velocities (2).
a - Petropavlovsk, b - Lipetsk, c - Magadan, d - Irkutsk, e - Chelyabinsk, f - Kursk.

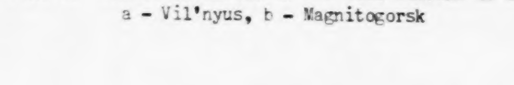

Fig. 5. Annual variation of the dust content of air.
a - Vil'nyus, b - Magnitogorsk

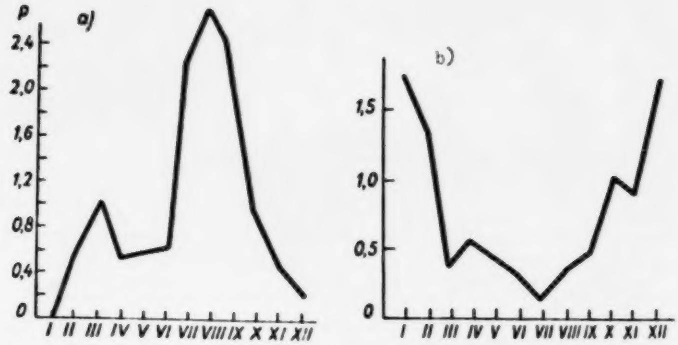

Fig. 6. Annual variation of sulfur dioxide concentration (P - ratio of mean monthly to mean annual concentration).

Studies have now been initiated at the Main Geophysical Observatory to evaluate the air pollution potential over the territory of the Soviet Union. The frequency of cases in which the wind velocity did not exceed 1 m/sec (conditions of air stagnation) was taken as one of the first characteristics of the air pollution potential. Data of meteorological observations for 5 years were used to plot a map of the frequency of days with wind velocities below 1 m/sec in January, April, July, and October (Fig. 7). As a result of the analysis of the maps, it was possible to distinguish the zones where the number of days with wind velocities of 0-1 m/sec in the course of 24 hours was less than 1 day (IV), from 1 to 5 days (II, III) and over 5 days (I).

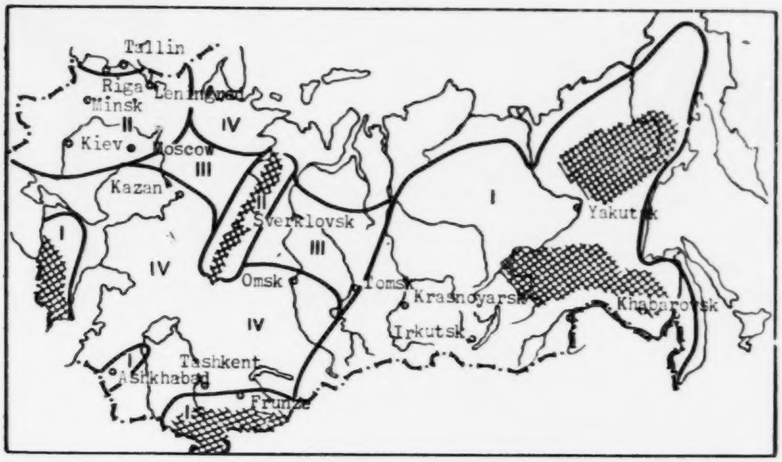
Tallin
Riga
Leningrad
Minsk
II
IV
Kiev
Moscow
III
Kazan
II
Sverdlovsk
III
I
IV
Omsk
Tomsk
Krasnoyarsk
Irkutsk
IV
I
Tashkent
Ashkhabad
Frunze
I
I
Yakutsk
Khabarovsk

Fig. 7. Regions with different numbers of days with wind velocities of 0-1 m/sec in the course of 24 hours (areas not included in the regionalization are crosshatched).

To estimate the pollution potential, it is useful to have data on the frequency, thickness and intensity of surface inversions, and also on the intensity of turbulent exchange on the territory of the Soviet Union given in [1, 2, 4, 5].

The results obtained are still insufficient for a detailed description of the air pollution potential in the country, but they have led to certain conclusions, some of which do not flow directly from knowledge of climatic conditions. The highest potential is observed in Eastern Siberia and the Far East, excluding the Pacific Ocean coast, and also in central Asia, where the danger of accumulation of pollutants in the air is compounded by a strong natural dust pollution. A region of appreciable air pollution potential is observed in the area of the Urals. It is characteristic that a tendency toward an increased potential is also noted in the western and northwestern regions of the European territory of the country, this being due to a high frequency of weak winds, primarily during the warm part of the year.

Consideration of the potential in the construction of new cities and industrial plants with the introduction of steps aimed at ensuring the purity of the atmosphere, and also the prevention of a dangerous buildup of noxious emissions in the air under unfavorable weather conditions may promote a decrease in the level of air pollution.

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*E. Yu. BEZUGLAYA, L. R. SONKIN*

# THE EFFECT OF METEOROLOGICAL FACTORS ON AIR POLLUTION IN THE CITIES OF THE SOVIET UNION*

The effects of meteorological factors on air pollution are considered on observation mateirals concerning contents of pollutants in the air in some towns of the USSR. It is shown that depending on wind velocity two concentration maxima of pollutants are discovered in the air, one at wind velocity of 0—1 m/sec, the other at 5—6 m/sec. For all this, the concentration maximum at wind velocity of 0—1 m/sec is expressed more clearly in the conditions of ground inversion, the maximum at wind velocity of 5—6 m/sec is seen in other cases. On the average, the air in town is more polluted in the presence of ground and low-lying elevated inversion, than in the absence of inversion in boundary layer.

An analysis of correlation coefficients between concentration values of air pollutants in different points of a town showed the presence of a trend to simultaneous change in air pollution. The cases of air pollution at high level in the whole town are considered. They are chiefly connected with light winds in boundary layer and stable stratification.

A parallel course of curves of pollution concentration in the air and light wind frequency is found in the annual course. For all this, the above-mentioned connection is expressed more clearly for carbon and nitrogen oxides which are emitted in large quantities by cars, that is in the lowest air layer.

The obtained results allowed to make preliminary conclusions on air pollution potential distribution on the territory of the USSR. For this purpose, data on frequency of light winds and stationary anticyclones are used. The zones of the highest potential are found in Eastern Siberia, Middle Asia, and in the regions of Urals.

The results of these studies are proposed to be used for the elaboration of air pollution forecast methods.

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* Editor's note: The abstract is presented as given in English with the original Russian article.